VOLUME 23, 1961/62, No. 8/9 pp. 221-292 Published 27th June 1962

Philips Technical Review

DEALING WITH TECHNICAL PROBLEMS
RELATING TO THE PRODUCTS, PROCESSES AND INVESTIGATIONS OF
THE PHILIPS INDUSTRIES

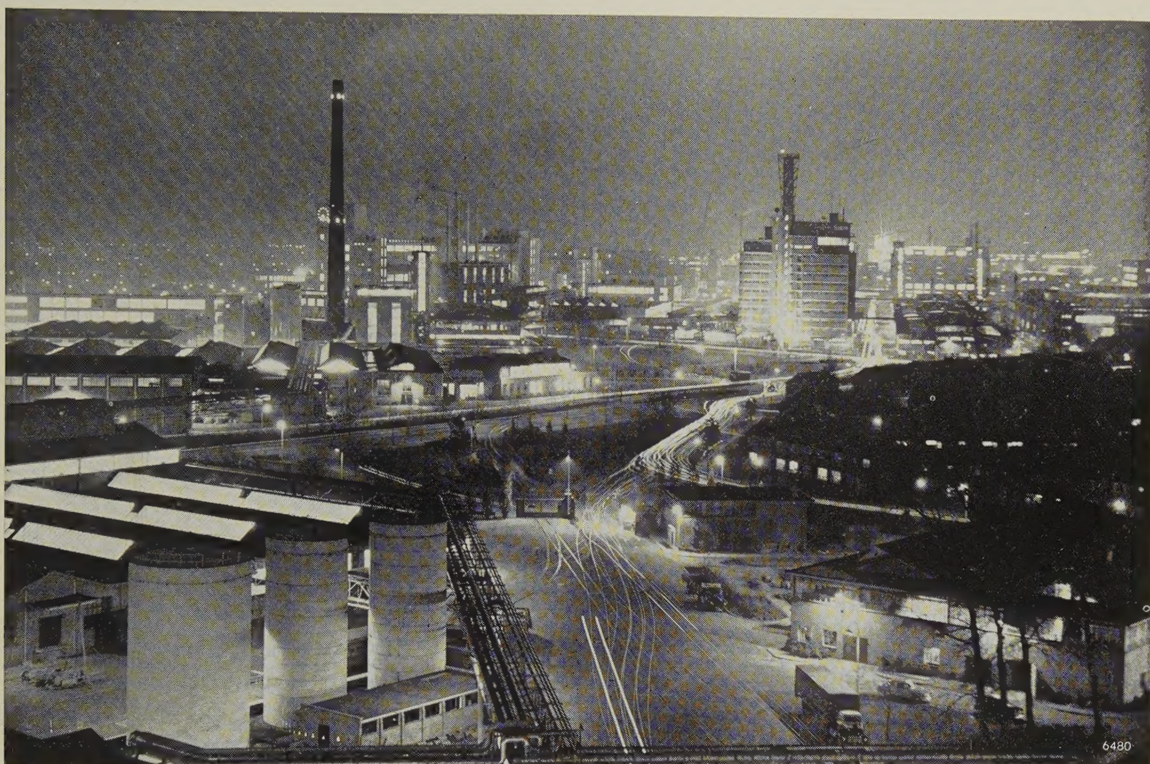


Photo M. Broomfield

Electric lamps were the first product of the Philips factories, and for nearly thirty years their only one. Although since then the research and production programme of the enterprise has expanded into numerous other fields, lamps and lighting have remained a corner-stone of Philips' activity. Some aspects of that activity are discussed in this number of our journal. The incandescent lamp, a product whose potentialities one would have thought had been exhaustively studied, is now seen to be open to further development, radically affecting the whole structure of the lamp. The sodium lamp too, whose construction had settled into a standard mould for many years, is again making headway as a result of fresh technical development; luminous efficiencies of 130 lumens per watt (disregarding ballast losses) or more can now be achieved with these lamps. Various modern light sources are reviewed in an article dealing with the present situation of road lighting. In the development of control gear (ballast) — a side-line of lamp manufacture — use is being made of "solid-state thyratrons", thus widening the useful scope of tubular fluorescent lamps. The concluding article deals with an example of the auxiliary equipment employed in the development of new types of lamp: a device is described which automatically plots the isocandela diagrams of beamed light sources.

This series of articles on episodes in the present work of Philips in the field of lighting is prefaced by an account of episodes from the period when it all started: a short history of the foundation of Philips' factories in 1891, documented by a selection of letters written by the founder, Gerard Philips.

THE BIRTH OF A LAMP FACTORY IN 1891

by N. A. HALBERTSMA *).

621.326.6(091)

The writing of history depends on a certain degree of good fortune. Anyone taking a momentous initiative, a man obsessed with an idea and struggling to give it form and substance, does not generally feel the urge to set down his motives on paper or to describe the conditions in which he embarks on his work, revealing the opportunities, desiderata and limitations of his day and age. Consequently the historian, who obviously cannot be content with extracting bare facts and relevant data from official documents, but who seeks to reconstruct motives and circumstances, usually has to rely on implicit information from many and various sources, in particular from contemporary records that chance to have been preserved.

A rich source of such information, bearing on the foundation of the Philips factories, was found in a letter-book containing copies of correspondence addressed to numerous people by the founder, Gerard Philips, in the period from April 1889 to April 1892. The book itself was destroyed in the bombing of the Eindhoven factories in 1942. Shortly before, however, typed copies had been made of all the letters in it that were still at all legible, the enterprise having by then already attained an age and size at which it could suitably meditate on its beginnings.

An attempt is made here, drawing on those early letters, and also of course on the fund of general data available on those years, obtained in part from books (see the references given at the end of the article), to present a broad picture of the circumstances in which a lamp works, the Philips factory, came into being in 1891. Some of the letters, which are interesting as historical documents, are reproduced *in extenso*.

The dawn of electrical engineering

The evolution of engineering since the 18th century has been based to a considerable extent on the exploitation of natural sources of energy (steam power, water power, gas, oil, etc.) and on the use of such energy sources which was made possible by the introduction of electricity. Steam and water power set the wheels of industry turning. Oil, gas and electricity, on the other hand, were used in the first place for *lighting*.

Oil lamps were of course known in antiquity. At the end of the 18th and the beginning of the 19th century a variety of refined forms came on the scene. In 1813 gas light made its appearance in the streets of London and Paris, and Berlin followed in 1826. Gas lighting in streets and houses was made possible by the *distribution* of the gas from the gas-works through a network of pipes all over the town. In London some 25 miles of gas mains had been laid by the end of 1815.

The fundamental discoveries relating to the generation of electricity and the production of electric light had already been made by this time. In about 1800 Davy had observed the intense light of the electric arc between two carbon electrodes, and in the first quarter of the 19th century there were repeated demonstrations of the light produced when a platinum wire is heated by an electric current. But as long as the current had to be supplied by a few hundred or thousand copper-zinc cells there could be no question of any practical application. Not until the second half of the 19th century, after the invention and perfection of the "dynamo-electric machine" (by Nollet, Holmes, Gramme, Siemens, etc.) was it possible to consider making use of the wide possibilities of the electric arc, with its great brightness, as a practical light source. Arc lamps were successfully introduced in lighthouses (for the first time in 1862 in the South Foreland Lighthouse), in military searchlights and for stage lighting.

In all these cases an electrical generator was used in conjunction with one single light source. The idea of *distributing* electricity in the same way as gas — i.e. to feed a number of dispersed public or private light sources from one generator — lay ready to hand, but was not so easy to realize as might now be thought. Jablochkoff took the first step in this direction in Paris, where he lit the Grands Magasins du Louvre in 1877 and the Avenue de l'Opéra and other streets in 1878 with large numbers of series-wired arc lamps of the kind he himself invented (the "Jablochkoff candle"). But his system proved to be far from ideal; the light fluctuated too much, and the use of arc lamps in series was certainly not a feasible method of domestic lighting.

*) Previously with N.V. Philips, Eindhoven, and emeritus professor of illuminating engineering at Utrecht.

In 1879 at Munich a new journal appeared under the name "Zeitschrift für angewandte Elektrizitätslehre", i.e. Journal of Applied Electrical Theory (or, as we would say nowadays, Journal of Electrical Engineering). This term was first used at that time by Werner Siemens in his proposal to found an association of workers in this field. He expected that such an association would help a large and solid structure to grow up on the foundations of the "applied electrical theory" already present. The association was indeed founded (the Elektrotechnische Verein Berlin, which merged with the Verband Deutscher Elektrotechniker in 1893), but before it could make any further progress in the application of electrical theory, one man — Thomas Alva Edison — startled the world towards the end of 1879 with a complete solution to the problem of "the distribution of electric light".

Edison's system of electric lighting

Edison had taken a comprehensive view of the problem and tackled all its aspects at the same time. Understandably he made no effort to improve the arc lamp, the smallest unit of which was still too powerful for domestic lighting and whose use involved so many complications. Instead he concentrated his attention on the *incandescent lamp*. He was not deterred by prevailing doubts, as e.g. expressed in the pronouncement of the British physicist, Sylvanus Thompson, in 1878 that "any system depending on incandescence will fail". After years of experiments, initially with filaments of platinum and later with carbonized bamboo fibres, with which Göbel had already experimented in 1846, he finally succeeded in making lamps possessing reproducible properties: a luminous efficiency of 0.2 candles per watt, a life [1]) of 200-300 hours, and a luminous intensity of either 10 or 16 candles. But this was only one side of Edison's work. The other was the detailed elaboration of the system of *parallel wiring* (in which direction, incidentally, Brush had already taken a tentative step at the end of 1878 in the arc-lighting of Wanamaker's Store at Philadelphia). Edison had realized that parallel wiring, where the current and not the voltage is sub-divided, was the only practical system in which lamps or other current-consuming devices could be separately switched on and off and which could thus lead to successful distribution. Edison's lamps were adapted to this system, having long thin filament wires to give them a *high* electrical resistance. This essential idea distinguished his lamps from those of Swan and others, who were still working on the idea of series wiring, and was set down by Edison in his most important patent, lodged on 10th Nov. 1879 (". . . electric lamps giving light by incandescence, which lamps shall have a high resistance so as to allow of the practical sub-division of the electric light . . ."). Under Edison's scheme the current from an electricity plant, where several dynamos, according to requirements, could be connected in parallel, would be carried by insulated copper rods, tubes or cables laid in the streets, and thence conducted by thinner branch lines into factories, shops and houses, just as in the case of the gas mains from the gasworks. Edison had to design every component of the installations required for this scheme. The lamp cap (or base) by which millions of electric lamps are still today fixed in their holders is the Edison screw cap. He invented the fuse, which automatically breaks the circuit in any branch of the network where serious overloads or short-circuiting occur. He improved the magnetic circuit of dynamos to such an extent that their efficiency rose from about 50% to 90% and more. There was also an electricity meter, which measured consumption by weighing electrolytic copper deposits, among the series of inventions with the aid of which Edison at the end of 1879 was able to present the world with a serviceable system of electric lighting.

While Edison was pushing ahead in the United States with the manufacture of all these components for his installations, he attracted attention to his system in Europe by a spectacular exhibit at the first International Electrical Exhibition at Paris in 1881 (where incidentally several other electric lamp manufacturers including Swan, Lane-Fox, Maxim and Siemens — see *fig. 1* — had their products on display). Edison demonstrated there a lighting system comprising 1000 lamps of 16 candle-power each, fed by his first large dynamo which, with its associated steam engine, weighed 25 tons and delivered 70 kW. His lamps at that time were already in mass production — in the first 15 months he had sold 80 000 at an initial price of about 3 dollars each. On 4th Sept. 1882 Edison started in New York to supply electricity on a large scale through the Pearl Street power station, first with one and later with six of the large aggregates mentioned. In 1890 this station, which had become world-famous, was destroyed by fire as a result of a short-circuit in

[1]) The precise meaning of these values is doubtful, since the concept "life" had not then been properly defined. In later years the "useful life" of carbon-filament lamps was specified as the number of hours the lamp burned until its light output had dropped to 80% of the initial value (owing to blackening of the bulb). The lamp would often burn for very much longer before its filament gave up.

the cables. Meanwhile, however, Edison Electric Illumination Companies had begun to supply electricity in many other large towns in the United States. In the years between, electric lamps had dropped in price to between 15 and 25 cents, their life had increased to 450 hours, and their luminous efficiency to 0.3 candles per watt. These were still the standard properties of carbon filament lamps in 1913 [2]).

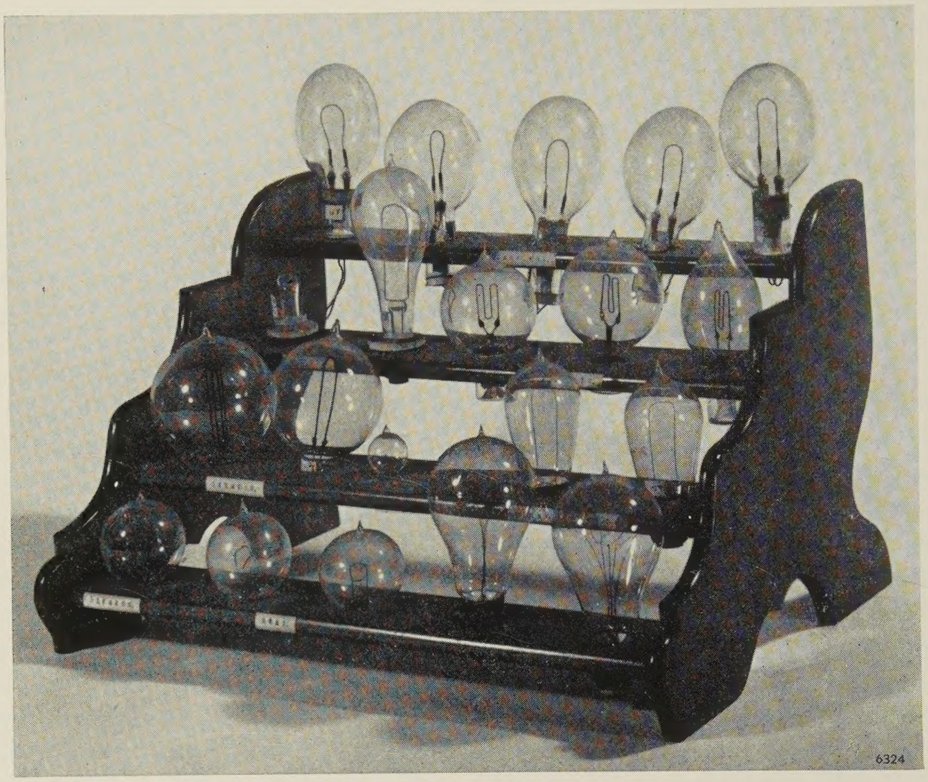


Fig. 1. Collection of 20 incandescent electric lamps, bought by the Teyler Foundation in 1881 at the Paris Exhibition, and including lamps made by Edison, Swan, Lane-Fox, Maxim and Siemens. (Reproduced by courtesy of Teyler's Museum, Haarlem.)

Examples of various types of incandescent electric lamps produced by different manufacturers in the first ten years are shown in *fig. 2*.

The development of electric lighting in Europe, more particularly in the Netherlands

After the Paris Exhibition of 1881 electrical engineering made vigorous headway in Europe too. Edison designed the first electric power station for London (Holborn) in 1882. Emil Rathenau, the German industrialist, acquired Edison's patents and in 1884 founded the "Deutsche Edison Gesellschaft für Angewandte Elektrizität", which later became the "Allgemeine Elektrizitätsgesellschaft" (A.E.G.). The existing firm of Siemens & Halske, specialists in telegraphic equipment (which they had started producing in 1847) embarked on the manufacture of dynamos and electric motors. Schuckert, Bergmann and Kolben, who had helped Edison in the development of installation equipment, went into production in Europe. Wherever electric mains had been laid, arc lamps too stood a better chance where larger light sources than the 16-candle-power incandescent lamps were needed. In Germany factories thus sprang up for making arc lamps and carbons (Schuckert), electricity meters (Aron), switches and lamp holders (Staudt and Voigt), and so on.

Elsewhere in Europe, notably in Great Britain, France, Switzerland and Italy, central power stations built on the Edison system paved the way to the distribution of electricity in the larger towns.

[2]) See A. Wilke, Die Elektrizität, 6th Edn. (edited by W. Hechler), Spamer, Leipzig 1914. — Lamps containing a "metallized" filament delivered 0.4 candles per watt.

A rough idea of the situation of electric lighting in 1891 is given by the following table of the numbers of lamps then in use:

	Incandescent lamps	Arc lamps
United States	2 800 000	23 500
London	600 000 *)	?
Paris	118 000	6 800
Berlin	70 000	3 000

*) A central power station was under construction for this number of lamps.

Although this brief review must naturally remain pitifully incomplete, let us also take stock very briefly of the development of electrical engineering in other fields than lighting. The large-scale use of electricity for chemical processes had long been under consideration. In 1789 Deiman and Paets van Troostwijk had discovered the electrolysis of water [3]), in 1807 Davy had prepared sodium and potassium by an electrolytic method, and in 1854 Bunsen had made aluminium in this way. By about 1840 the technique of electroplating, developed by several researchers, was in use in industry. The application of electricity for transmitting and distributing mechanical energy also began to come to the fore in the 'eighties. Here, however, the situation was still uncertain. Attempts were also being made to meet local requirements of mechanical energy by means of small prime movers, e.g. small hot-air engines. And even as regards the possibility of *centralized* power supply, electricity had its competitors: in Paris at that time, Popp built an installation for supplying compressed air to users all over the city through a network of pipelines.

A milestone was reached in the transmission of mechanical energy by electricity when A.E.G. and the Oerlikon Engineering Works demonstrated the transmission of 100 HP by means of three-phase alternating current at the 1891 International Electrical Exhibition at Frankfurt-on-Main. The generator was 110 miles away at Lauffen on the Neckar. This ushered in the era of alternating current, and the D.C. system adopted by Edison was gradually eclipsed.

[3]) J. R. Deiman and A. Paets van Troostwijk, Beschrijving van eene Elektrizeer-Machine en van Proefnemingen met dezelve in het werk gesteld (Description of an Electricity Machine and of experiments performed with the same), Amsterdam 1789.

To conclude this introduction let us take a look at events in the Netherlands.

In 1878 Willem Smit, whose name is still connected with three major electrical firms in the Netherlands, built his first dynamo at the age of eighteen, after having seen in the Leygraaf Hotel at Rotterdam an arc lamp run from a dynamo built by Gramme. With his own dynamo, and a Hefner-Alteneck arc lamp, Smit was able to light his father's rivet factory at Slikkerveer. This aroused such interest among neighbouring factory-owners that he received orders for similar installations.

In 1882 this pioneer of electrical engineering in the Netherlands, together with his brother-in-law Adriaan Pot, founded a company for producing electric lighting equipment and trading in electrical appliances and related articles. The new enterprise received orders for lighting ships with parallel-wired incandescent electric lamps, and it hired out installations for public festivities, exhibitions, etc.

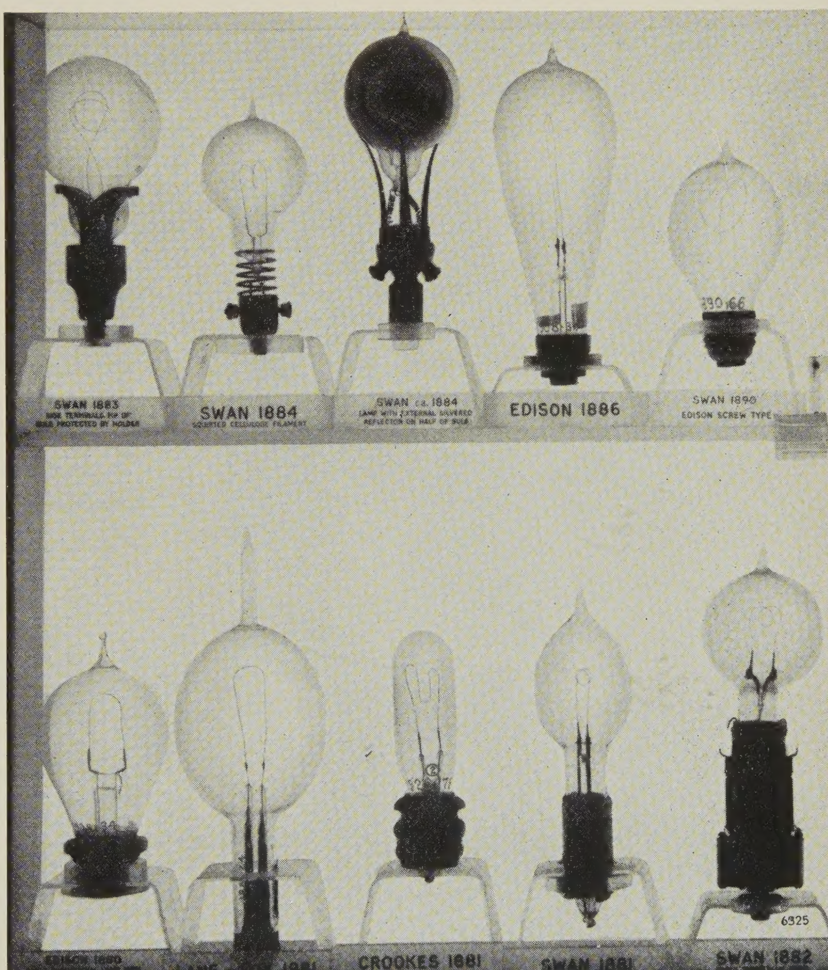


Fig. 2. Electric lamps of types made between 1880 and 1890, in chronological order. (By courtesy of the Science Museum, London.)

Even the lighting system installed in the Coomans Hotel at Rotterdam (1884), comprising one arc lamp of 60 A and 120 Swan incandescent lamps of 35 candle power, was on hire. The hotel paid a monthly rent corresponding to the amount it would otherwise have spent on gas lighting.

In 1886, the power station of Willem Smit & Co. — the first in the Netherlands — was put into operation at Kinderdijk. The station started with two DC dynamos of 110 V, 200 A, and later an alternating-current generator was added for lighting the neighbouring village of Krimpen via a cable under the river Lek. The station operated on very simple lines. At midnight the lights went out, but if there was a celebration somewhere a few hours' extension could be obtained "if requested in good time". The tariff charged was based on the number of lamps installed, and amounted to 2.50 guilders monthly for every lamp of 35 candle-power.

Other details that throw light on the situation in the Netherlands and Europe in the years that Gerard Philips' plans matured will emerge from the following account of his life.

Gerard Philips' first steps in electrical engineering

Gerard L. F. Philips, born in 1858, was the elder son of B. F. D. Philips, a manufacturer, banker and owner of the gas-works at Zaltbommel. From 1876 he studied first civil engineering and later mechanical engineering at what was then called the "Polytechnische School" at Delft. He showed keen interest in the developments of applied electricity, both in the Netherlands and abroad. While he was still at secondary school in Arnhem he had attended a course of lectures and demonstrations on this subject at the "Wessel Knoops" Physical Society. The lecturer, who held him enthralled, was a young teacher of the name of Dr. H. A. Lorentz — the later renowned physicist and Nobel Prize winner.

At Delft the new subject was not yet on the curriculum [4]), and when Gerard, after graduating in mechanical engineering, decided to apply himself to electrical engineering, his obvious course was to try to acquire more knowledge through practical experience. In 1883 he therefore set out as a young engineer for Glasgow, where he supervised the installation of an electric lighting system on the S. S. Prins Willem van Oranje for the Zeeland Shipping Company. After that he worked for nearly a year in the laboratory directed by the distinguished physicist William Thomson, later Lord Kelvin, whom he assisted in the development of electrical measuring instruments.

He was then invited by the managing director of the Brush Electrical Company, manufacturers of dynamos and arc lamps, to go to Berlin and prospect the market there for the Brush products. It is not surprising, in view of the strong position which the German firms A.E.G. and Siemens occupied on their home market, that this assignment yielded few positive results.

Back in England, Gerard sat in 1887 the examination of the City and Guilds of London Institute in "Electric lighting and transmission of power and telegraphy", and was awarded first prize, a silver medal (*fig. 3*). He then settled in London for a time as the representative of several German electrical firms.

The next episode in the life of Gerard Philips, and the experience it gave him, undoubtedly did much to form in his mind the plan of making electric lamps in the Netherlands. Emil Rathenau, the managing director of A.E.G., appointed him the agent of that firm in Amsterdam. His assignment went further than simply procuring orders for electrical machines and installations. The municipal corporation of Amsterdam intended to grant a concession for the building and operation of a power station, and Rathenau was particularly keen to obtain that concession. Gerard had to win over both the corporation and leading figures in financial circles for Rathenau's tender. It was no easy task, for on the one hand there were differences of opinion

[4]) The first course of lectures on electrical engineering was given at the Technische Hochschule at Darmstadt in the winter term of 1882/1883, by Professor Dr. E. Kittler.

Letter I (letter-book p. 146).
(Translated from the original German.)

Hotel Mille Colonnes, Amsterdam. 24.9.1890

Herrn Direktor E. Rathenau,
A. E. G.,
Berlin-N.

The proposal of the Municipal Executive to grant a concession to "Electra" was approved at today's meeting of the City Council.

This therefore concludes my efforts to procure this concession, and not in the way I had hoped.

Several councillors, members of the Public Works Committee, informed me confidentially that they really regretted having to grant a concession to "Electra", and that if your price had been not more than a few cents higher than that quoted by "Electra" they would certainly have given you preference. The price difference now, however, was too (considerable *)).

Yours faithfully,

G. L. F. Philips

*) Not clearly legible.

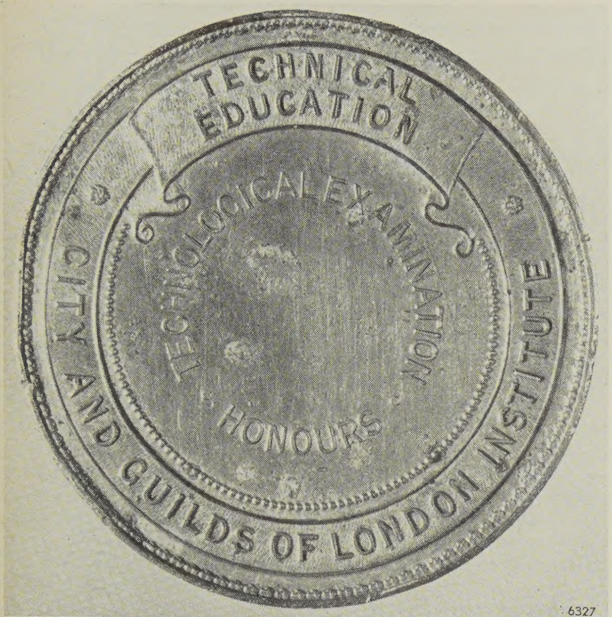


Fig. 3. Silver medal awarded to Gerard Philips in 1887 for passing an examination of the City and Guilds of London Institute with honours.

in the corporation about the form and terms of the concession and about the relative merits of municipal control and private enterprise, and on the other hand Rathenau put his demands very high as regards the electricity rate. He asked for 60 cents per kWh, and in letters to Berlin — which were preserved in the letter-book referred to — Gerard fought stubbornly to persuade Rathenau that he ought to reduce this price. Rathenau, however, refused to yield. When the concession was dealt with by the City Council, they decided to grant it to a competitor who was prepared to supply the electricity at 46 cents per kWh (see *letter I*, of 24th September 1890).

Soon afterwards Gerard's work for the A.E.G. came to an end.

Prelude to the foundation of the factory

Gerard Philips was now 32 years of age, and it was time to decide how and where he was to earn his living by electrical engineering in a way that would give him personal satisfaction. His difficult assignment under A. E. G. must have strengthened his self-confidence and also have aroused the desire to be independent and to carry the full responsibility for an enterprise himself. Would not the Netherlands, in view of the rapid advancement of electrical engineering, soon need an electrical industry of its own? And would there not in the first place be a demand for the production of electric lamps, which have a limited life and therefore called for constant replacements?

Gerard Philips was not the only one to whom this idea occurred; the optimistic expectations for electric light were too widespread for that. In 1890 four electric lamp factories were already established in the Netherlands, but the correspondence shows that Gerard regarded only one of them as a serious competitor, namely Goossens & Pope, a factory founded in March 1889 at Venlo by the Englishman Pope. The other three: Boudewijnse at Middelburg, De Khotinsky at Rotterdam and Roothaan & Alewijnse of Nijmegen, soon succumbed to the same difficulties that Gerard Philips was later to come up against — and to overcome.

At the Brush Electrical Company, Gerard had gained some experience of the manufacture of incandescent lamps, and he knew that the most important factor was the uniformity of the cellulose carbon filament. His first work towards the realization of his aim (which he started before he left the employment of A.E.G.) was therefore in the chemical field. He equipped a wash-house in his parents' garden at Zaltbommel as a "laboratory" (*fig. 4*) and as soon as he thought he had succeeded in producing a carbon filament of good quality he started advertising in the "Elektrotechnische Zeitschrift" and the "Electrician" for a works manager.

Fig. 4. Gerard Philips experimenting in his home-made laboratory at Zaltbommel in 1890.

Letter II (letter-book pp. 149/150).

Hotel Mille Colonnes, Amsterdam. . . *) November 1890

C. J. Robertson Esq.,
Middelburg.

Sir,

I duly received your favour of the 6th inst. I still fail to see any decrepancy between my advertisement and conversation, in fact, I am inclined to think, that, if any, the want of agreement is on your side.

It is perfectly true that our plans are not yet settled but we thought that your knowledge of Dutch lamp making works and prices would assist us herein, and that at the same time, we would be able to enter into an agreement with you. We turned to you because you have a knowledge of the country and the language, and for no other reason, for, as I frankly told you, Mr. Boudewijnse's lamps hardly enjoy as good a reputation overhere as those of several other Dutch and German makes.

We have received quite a large number of applications where amongst from gentlemen who are very well qualified.

It is our intention to start a factory of 1000 lamps daily output, but we would at first make only 500 lamps a day, making the building and engine large enough for 1000 lamps. For a factory of this size we can supply the required capital ourselves, and we estimate this, when the output of 1000 lamps daily has been reached, at F. 75.000.— viz.:

total cost of building and plant F. 37.000.—
total working capital F. 38.000.—.

An increase of the working capital, above this cipher, would not . . . *)

As advertised, we want to contract with an electrician (or as I would now put it, after our recent conversation, an electrical engineer), able to plan and fit up the factory and to manage the works. We are prepared to pay him, in addition to a fixed salary, a certain part of the net profits, but we are quite willing to consider any other basis of agreement.

I am, however, aware that it offers important advantages to start at once on a large scale, say with a daily output of 2500 lamps. Since we have very good connections, it is quite possible that we may be able to form a syndicate for this purpose. In such case it would be advisible to allot the expert a certain number of shares in the Company to . . . *) for his goodwill and his patents or what is equivalent to this. This, however, must be done by special separate contract since the Dutch laws don't allow such seemingly gratuitous allotments to be incorporated with the articles of association.

But in order to be able to form a defined opinion of the relative advantages of the manufacture of lamps on different scales, it would interest us to have your calculation of the rentability of the lamp making business for an output of:

1) 1000 lamps daily (at first only 500 daily but building an engine large enough for 1000),
2) 2500 lamps daily.

We assume that lamps of all current C.P. (up to 100 C.P.) and E.M.F. have to be made, and we premise certain unit prices of materials, coals and labour. In the first case I would leave out any remuneration of the partners, accept any salary to be claimed by you in accordance with . . . *) proposals. In the second case a remuneration of the management in accordance to your own views or proposals should be drawn into account.

If we start a lamp factory of 500-1000 lamps daily on our own account, we will probably chose Breda, where we can buy a plot of land for F. 1000.—. The wages there are about as in Middelburg.

I shall be pleased to know your terms and I hope there is no objection on your part to supply an estimate on the lines above mentioned. In such case I could hardly ask you to do so at your earliest convenience.

Yours truly,

G. L. F. Philips

*) Illegible.

Letter III (letter-book p. 154).

Hotel Mille Colonnes, Amsterdam. 14.11.1890

M. E. Bailey Esq.,
London, E. C.

Dear Sir,

I duly received your application of Oct. 20, in answer to my advertisement in the Electrician of October 17, address 943 Electrician's Office.

You will understand that I have received a large number of applications both from England and the Continent, and I am now in correspondence with several lampmaking electrical engineers on this matter.

I intend to start an incand. lampfactory in Holland, with a daily output of 1000 lamps, starting however with less, but working up to this number.

I am able to produce extremely homogeneous and equal cellulose filaments on a business scale, and I am not so much in want of special details of manufacture, patented or not, of which, of course, any man, engaged in lamp-making, has quite a number to himself; what we want is a man quite competent to carry out and work a modern lamp factory on thorough business principles, in other words to make first-class lamps on a sound business scale in as cheap and efficient a way as possible.

In your letter you state that you were able to make lamps for four pence three farthings each. How do you understand this price? Are you prepared to say — and eventually to guarantee — that this is the net price inclusive of (London) labour, salaries, rent, amortisation, etc.? Today, of course, allowance has been made for the higher prices of platinum. You will excuse my feeding some doubt, and more so since you work (?) with platinum and mercury glass airpumps, two things, which in the States they are trying to do away with.

I shall however be glad to receive some information on these points and to know whereon your data are based. And also what the cost of establishment of a factory for 1000 lamps daily would be on your plans. I shall also be glad to know your terms for an engagement.

I can give you many references with regard to myself.

I shall have to run over to London before long and would seize the opportunity to call upon you, if you are able to give me reliable data and facts concerning your ways of lampmaking.

I hope to receive your reply and proposals at an early date.

Yours truly,

G. L. F. Philips

This appears from several of his letters addressed to applicants for the post, and his letters also show that he was contemplating a factory with a final output of 1000 lamps daily. After abortive negotiations with an English candidate, who demanded co-partnership in the firm (*letter II* of about 9th November 1890), and with yet another Englishman (*letter III* dated 14th November 1890), he entered into more decisive arrangements with the "production chief" or foreman of a small lamp factory at Brussels, which had had to close down. In a letter dated 30th December 1890 Gerard invited this candidate, E. Woschke, to come to Zaltbommel for discussions (*letter IV*). It was evidently his intention — as in previous contacts — to test his ideas on production against those of people with practical experience The letter in question also reveals that J. J. Rees

Letter IV (letter-book p. 163).
(Translated from the original German.)

Hotel Mille Colonnes, Amsterdam. 30.12.90

Herrn E. Woschke,
Brüssel.

I duly received your favour of the 10th inst. but was unable to let you know anything definite earlier. I am at present very busy working out various details of lamp making. First I am now making a clean and chemically pure filament. Then, as regards the fabrication of . . . . *) there are several details which do not appeal to me at all. Like most lamp makers I want to make the connection between the carbon and platinum wires electrically; this makes much faster evacuation necessary. The Seel pumps take an abnormally long time; I had the opportunity recently to inspect and make sketches of the pumps in the Roothaan and Alewijnse factory. These take less than half an hour . . . . *) in Venlo evacuation takes only half an hour. This means that considerably less machine power is needed than in the Seel factory. On this part I have exact specifications for the Nijmegen and Venlo factories. I also intend to use accumulators, etc.

I shall not run the enterprise with Mr. Reese, but with my father's assistance. Of course, quite differently from the Seel people, as economically as possible, with no nonsense, and with the least possible loss at the start.

I should now like to have a decisive talk with you, in my father's presence. You may be sure that you are dealing with decent people. My father would like you to come to his house at Zaltbommel. Any day suits us, and of course we shall pay your expenses.

If you take the 6.27 a.m. train from Brussels, you travel via Antwerp and arrive at 8.27 in Roosendaal, at the Dutch customs. You change there and take the 8.50 to 's-Hertogenbosch, arriving at 10.02. You wait there for the 10.33 train to Zaltbommel or Bommel, arriving at 10.51 in the morning. Altogether, then, only 4½ hours. You will find an omnibus at the station.

I hope to hear from you soon what day you will be coming. You can leave again in the evening at 6.37 and will be back in Brussels at 11.14.

Yours truly,

G. L. F. Philips

*) Illegible.

of Amsterdam, an acquaintance of Gerard's who was to be a partner in the projected enterprise, had dropped out, but that Gerard could now count on financial support from his father.

The discussion at Zaltbommel that took place shortly afterwards led to agreement. With effect from 1st January 1891, Woschke was engaged at a monthly salary of 120 guilders. Pending a decision on the place of establishment and the purchase either of a plot of land or, even better, of existing premises, Woschke remained in Brussels where he received a sort of retaining wage.

One of the places Gerard had in mind as a likely place of establishment was Breda (see letter II), where a plot of land was available for 1000 guilders and where wages were apparently not very high. In February 1891, however, he came upon the

Letter V (letter-book pp. 168/169).
(Translated from the original German.)

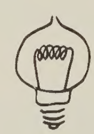
Hotel Mille Colonnes, Amsterdam. 28.2.1891

Herrn E. Woschke,
Brüssel.

I duly received your letters of the 10th and 26th inst. and thank you for your answers to my various questions. I still do not need you at present. I am not nearly as far as you seem to think, and you will certainly help in setting up the factory, when I can make good use of your services. For various reasons matters have been postponed, and I am still negotiating the purchase of existing factory premises. I have the chance of buying a very nice factory, only a few years old, a single-story, rectangular building, equipped with steam engine and boiler; but the building is entirely of brick and iron, and I am now afraid that the iron may influence the instruments; I should like to have your opinion on that point. The factory measures 18 × 20 M. I am off to Zalt Bommel today and shall write to you from there.

I am sorry that I cannot ask you, as I had definitely hoped, to come to Holland yet; the situation where you are is certainly not pleasant, but I could not let you come to Holland before I have rented or purchased a proper building somewhere. That should soon be possible; I hope to be able by the middle of next week to invite you to come here to give your opinion on the building. Apart from the premises mentioned above, I am negotiating for two other buildings in another town, but I would like to rent or buy steam power at the same time.

I now have much further information regarding the Venlo factory. One man there evacuates 500 to 600 lamps daily, i.e. he turns the valves, for there is no question of lifting weights. He receives 9 . . . . *) per 100 lamps. I shall try to become acquainted with these pumps, for you appreciate that this is very different from Seel. The man concerned has one bench of 36 lamps under him; three small or two large lamps on each pump. They are Sprengel pumps. The Venlo lamps are well known, and are much used here; the factory was doubled in size last summer; I know the lamps, and they have spiral carbon filaments that look like this:



That has the effect that the filament is not seen so sharply, the light appears to be more concentrated, more like a gas flame. I can have the man who made these carbons for 12 guilders a week; he is skilled carpenter and a clever fellow.

You'll probably still have some of that uncarbonized wire from Venlo. I should like to have a small piece to compare with my wire. In Venlo the carbon filaments are left all night over white hot . . . . *). They use blast-furnace coke.

As I said, I hope I shall need you next week for deciding on the factory premises. Very soon after that you will be able to move here, but at present, as you will understand, that is not yet possible.

Yours truly,

G. L. F. Philips

P.S.
In Venlo they had two German glass-blowers at the beginning, but not now. Everything today is done by girls. That makes a considerable difference. We shall have to try that ourselves later in order to remain thoroughly competitive. The Venlo factory is a sound business, quite different from Seel. They do good business and we must try to follow their example.

*) Illegible.

vacant buckskin factory of Schroeder & Weijers in Eindhoven (*fig.* 5), which was equipped with a boiler and a 40-HP steam engine. On 28th February 1891 he mentioned this opportunity to Woschke (*letter V*) and on 16th May 1891 he bought the factory for 12 150 guilders.

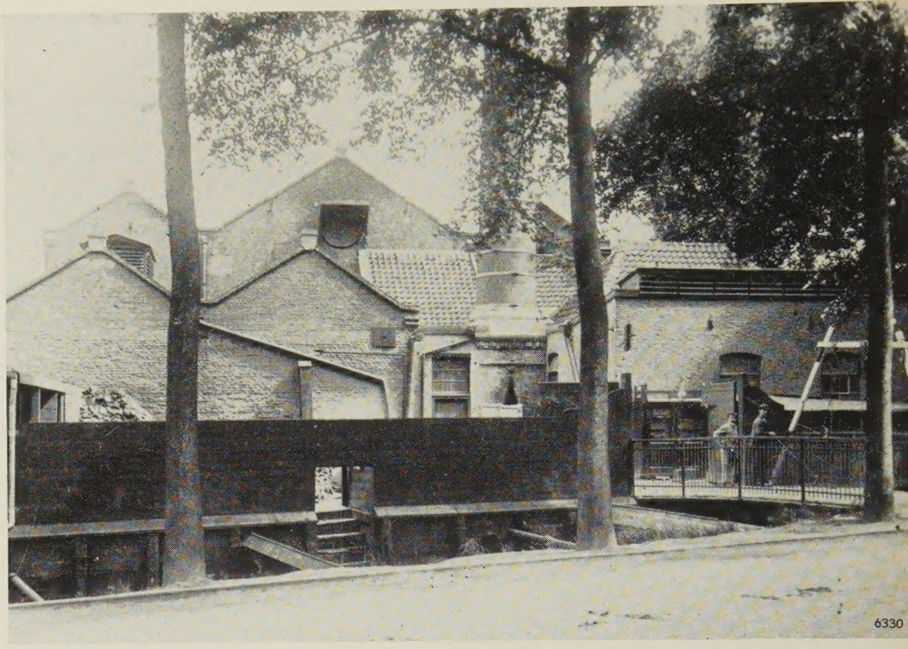


Fig. 5. The factory of Philips & Co. in 1891.

That letter reveals how very busy Gerard had been meanwhile with the technical problems, whose solution he regarded as essential to the success of his enterprise. Apart from fabricating a homogeneous carbon filament, he was particularly concerned with the evacuation of the bulbs and with glass-blowing. At that time lamp manufacture was an industry in which wages represented a relatively high proportion of the costs of production. It was therefore imperative to shorten the production time per lamp and to simplify the operations, so that as much as possible of the work could be done by girls as cheap labour.

The group photograph of the entire personnel taken in the first year of business (see *fig. 6*), shows that Gerard lost no time in putting the latter principle into effect.

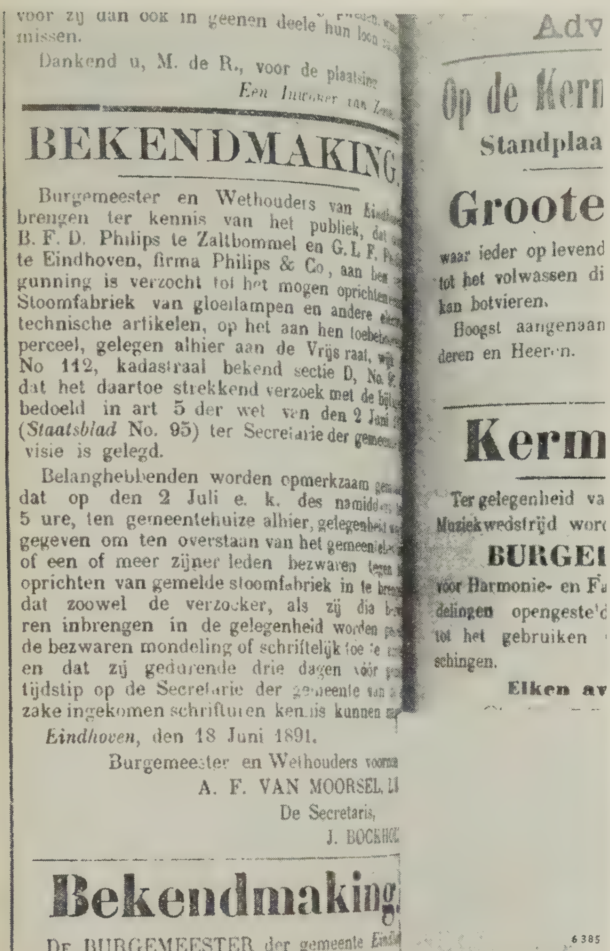
The beginnings of Philips & Co.

On 15th May 1891 the firm of Philips & Co. was established at Eindhoven (*fig.* 7) with G. L. F. Philips as the working partner and his father, B. F. D. Philips, as sleeping partner. The capital provided by the latter was 75 000 guilders. Woschke was at last able to move to Eindhoven and Gerard at once set about overhauling the steam installation, which had been idle for more than a year, and to place the necessary orders, first of all for electrical equipment.

Fig. 6. Group photograph of the entire personnel of Philips & Co. in 1891. Woschke — who was dismissed at the end of 1892 — is the man wearing a cap.

He asked for quotations from several firms, including Mijnssen & Co. of Amsterdam, the Dutch agents of A.E.G. Their quotation arrived on 22nd May, and on 23rd May he sent off an order for three dynamos, one large and two smaller ones (see

letter VI). He asked for shipment within fourteen days. On 25th May he ordered from Hartmann & Braun of Frankfurt-on-Main a whole series of measuring instruments, including an aperiodic precision voltmeter, four ordinary voltmeters, a portable test voltmeter with two scales, a wide-range ammeter (200 A) and four narrow-range ones (5 A),



voor zij dan ook in geenen deele hun loca... missen.

Dankend u, M. de R., voor de plaatsing
Een Ingezeter van Z...

BEKENDMAKING

Burgemeester en Wethouders van Eind... brengen ter kennis van het publiek, dat B. F. D. Philips te Zaltbommel en G. L. F. Ph... te Eindhoven, firma Philips & Co, aan hen ver... gunning is verzocht tot het mogen oprichten... Stoomfabriek van gloeilampen en andere ele... technische artikelen, op het aan hen toebeho... perceel, gelegen alhier aan de Vrijs raat, wijk No 112, kadastraal bekend sectie D, No... dat het daartoe strekkend verzoek met de bijl... bedoeld in art 5 der wet van den 2 Juni... (*Staatsblad* No. 95) ter Secretarie der gemeen... visie is gelegd.

Belanghebbenden worden opmerkzaam gem... dat op den 2 Juli e. k. des namidd... 5 ure, ten gemeentehuize alhier, gelegenheid... gegeven om ten overstaan van het gemeente... of een of meer zijner leden bezwaren tegen... oprichten van gemelde stoomfabriek in te bren... dat zoowel de verzoeker, als zij die b... ren inbrengen in de gelegenheid worden ge... de bezwaren mondeling of schriftelijk toe te ... en dat zij gedurende drie dagen vóór ... tijdstip op de Secretarie der gemeente ... zake ingekomen schrifturen kennis kunnen ...

Eindhoven, den 18 Juni 1891.

Burgemeester en Wethouders voorn...
A. F. VAN MOORSEL, L...
De Secretaris,
J. BOCKHO...

Bekendmaking

DE BURGEMEESTER der gemeente Eind...

Adv...

Op de Kern...
Standplaa...

Groote
waar ieder op levend... tot het volwassen di... kan botvieren.
Hoogst aangenaan... deren en Heeren.

Kerm...
Ter gelegenheid va... Muziekwedstrijd wor...
BURGE...
voor Harmonie- en Fa... delingen opengeste'd tot het gebruiken ... schingen.
Elken av...

Fig. 7. Announcement of the application by the firm of Philips & Co. for a licence to "set up a steam factory for incandescent lamps and other electrotechnical articles", dated 18th June 1891 and published in the "Peel- en Kempenbode".

a "Wasservoltameter", a direct-reading tension galvanometer and a measuring bridge. Gerard gave a reference and held out the prospect of further regular orders, but demanded shipment of the instruments within three weeks. Everything points to the go-ahead lines on which Gerard was determined to build up his enterprise. When it appeared that the A. E. G. needed a longer delivery time for the smaller dynamos, Gerard cancelled that part of his order and promptly turned to other suppliers who, as he wrote, "took more trouble with the smaller machines".

Nowadays a man starting up in business would buy a car. The automobile was still right at the beginning

Letter VI (letter-book p. 170).
(Translated from the original Dutch.)

Philips & Co. 23.5.1891

Den Heeren Mijnssen & Co.,
Amsterdam.

Dear Sirs,
We are in receipt of your favour of 22nd inst., and request you to supply us with the dynamos mentioned below, on condition however that we receive within eight days the necessary drawings with dimensions for laying the foundation and arranging transmission, and further that the dynamos hereby ordered are dispatched to us within fourteen days.
We order:

1 G 200, shunt, for 150 Volts and 170 Amperes, complete with regulator.
1 NG 25, compound, for 300 Volts and 10 Amperes, complete with regulator.
1 S 15, for 200 Volts and 7 Amperes, complete, but without regulator.

All at the terms of payment mentioned in your letter.
The speed of the above machines should not exceed the figures mentioned in the price list; in this connection we request you to send us the correct data together with the drawings referred to.
The compounding of the machine must be very good, as good as can be expected from a first-class compound dynamo.
We trust that you will execute this order to our complete satisfaction.

Yours faithfully,
Philips & Co.

Letter VII (letter-book p. 208).
(Translated from the original Dutch.)

13.7.1891

Den Heer Deumer Cramer,
Utrecht.

Dear Sir,
I have your bicycle back in my possession, but the bell is missing. I am still not satisfied with the repair, however, and I am therefore returning the machine once again. I am not prepared to accept a machine which is defective in one of its main parts. I am paying good money and expect a good machine for it, without the slightest defect. That seems to me to be no more than reasonable. On the whole I cannot say that your machine behaves as a first-class machine should. I know several people here who have not yet had any trouble after long use, and your machine already shows defects after a short trial. The saddle bar has a tendency to twist, and pulls the connecting rod between the bars backwards, so that the frame bars under the saddle bend over backwards; it seems to me that this is due to a weak (or faulty) construction. At the top of the front fork a seam is already noticeable where the paint . . . . *) obviously caused by play in those parts.
I request you therefore to supply me as soon as possible with a well-built machine, without a single defect, as otherwise I shall have to turn elsewhere. I have been asked by various people whether I can recommend the machine, but what am I to answer under these circumstances?

Yours etc.
G. L. F. Philips

*) Illegible.

Letter VIII (letter-book p. 248).
(Translated from the original German.)

30.7.1891

Herrn W. Müller,
Brüssel, N.

We duly received your letter of 27th inst. We are prepared to pay you a wage of Frs. 45 per week for making the new pumps. Incidentally, you may depend on it that you are dealing with decent people. If we are satisfied with you, as we expect to be after what we have heard from Mr. Woschke, your position here will certainly be a very assured one, and we shall pay you a very fair wage. You are the first here, and that has its advantages! In Holland we do not like constant changes of personnel; when we have good people we keep them. Binding arrangements are not entered into here for the good reason that it is unpleasant to have to go on working together when one party is not pleased with the other. We believe, however, going by what Mr. Woschke says, that this will not be the case with us.

Looking forward to your arrival, we remain,

Yours truly,

Philips & Co.

Letter IX (letter-book p. 356).
(Translated from the original German.)

29th October 1891

Herrn H. Jahrke,
Frauenwald.

We have an immediate vacancy for an efficient and steady glass-blower for making and repairing our mercury pumps. We should fix his salary at 20 guilders a week and would pay his travelling expenses. It is essential that he should be able to start immediately. We should be very obliged to you if you could help us find the man we want. He must, of course, be of sober and decent habits. If he is satisfactory, his position with us would certainly be a very assured one.

Thanking you in advance for a reply, we remain,

Yours faithfully,

Philips & Co.

Letter X (letter-book p. 315).
(Translated from the original German.)

1st October 1891

Herrn Albert Voss,
Ellrich a/Harz.

For cementing-in our incandescent lamps we require a special plaster of Paris which must be very hard, but should not take too long to harden properly. Nor should the plaster expand too much.

Furthermore we shall soon need a new floor for our mercury-pump department, and may perhaps decide to give your floor plaster a trial.

We therefore request you to supply us with information, prices and samples for both purposes.

How long can the lamp plaster be stored? Please let us have your keenest prices.

Yours faithfully,

Philips & Co.

Reference banker J. H. Stein, Cologne.

of its development in those days (if we disregard the cumbersome steam carriage), but Gerard did order a modern means of transport — a bicycle. The result was not to Gerard's liking, and we can see from his letter to the Utrecht importer who delivered the machine just how angry he could be over slovenliness and unreliability (*letter VII*).

After the electrical equipment he turned his attention to the pumps for evacuating the lamp bulbs. The equipment then available in this line was intended more for physical experiments on a laboratory scale, and was not suitable for evacuating large numbers of lamps simultaneously and quickly. Gerard therefore tried to engage someone with experience in this field, and on 30th July 1891 he wrote to a certain W. Müller in Brussels, who had been recommended by Woschke (*letter VIII*). The letter gives the impression that Müller was very keen on obtaining a permanent post, but Gerard considered that a satisfactory employer-employee relationship was more important than a binding contract. Apparently he was right, for three months later, on 29th October 1891, Gerard was again urgently seeking a man for the same post, this time through a business relation in Germany (*letter IX*). In the letter in question Gerard insists rather significantly that the man should be "steady" and "sober" (presumably in the meaning of not drinking to excess) and we can only guess that this was perhaps the reason for the previous disappointment. As appears from the letters which Gerard wrote on 16th and 21st November to two applicants for the post, this was evidently a stumbling block in Gerard's work. On 29th February 1892 he was again writing to one of these applicants, because the post — meanwhile occupied by someone else — had again fallen vacant.

Fig. 8 gives an idea of what the evacuating system for carbon-filament lamps must have looked like in those days.

The lamp bases — originally made of plaster of Paris, cast in zinc moulds in which the brass screw-thread mantle and the central contact had been placed beforehand — were not made by Gerard himself. The Boudewijnse lamp factory at Middelburg, which had failed as such, had turned to the specialized production of lamp caps, one improvement introduced being the sealing together of the shell and cap contact by means of "Vitrite", an insulating glass compound. On 1st October 1890 Gerard asked for a quotation from "The Vitrite Works" — apparently with good results, for the caps of nearly all Philips incandescent lamps are still made today by the Middelburg factory.

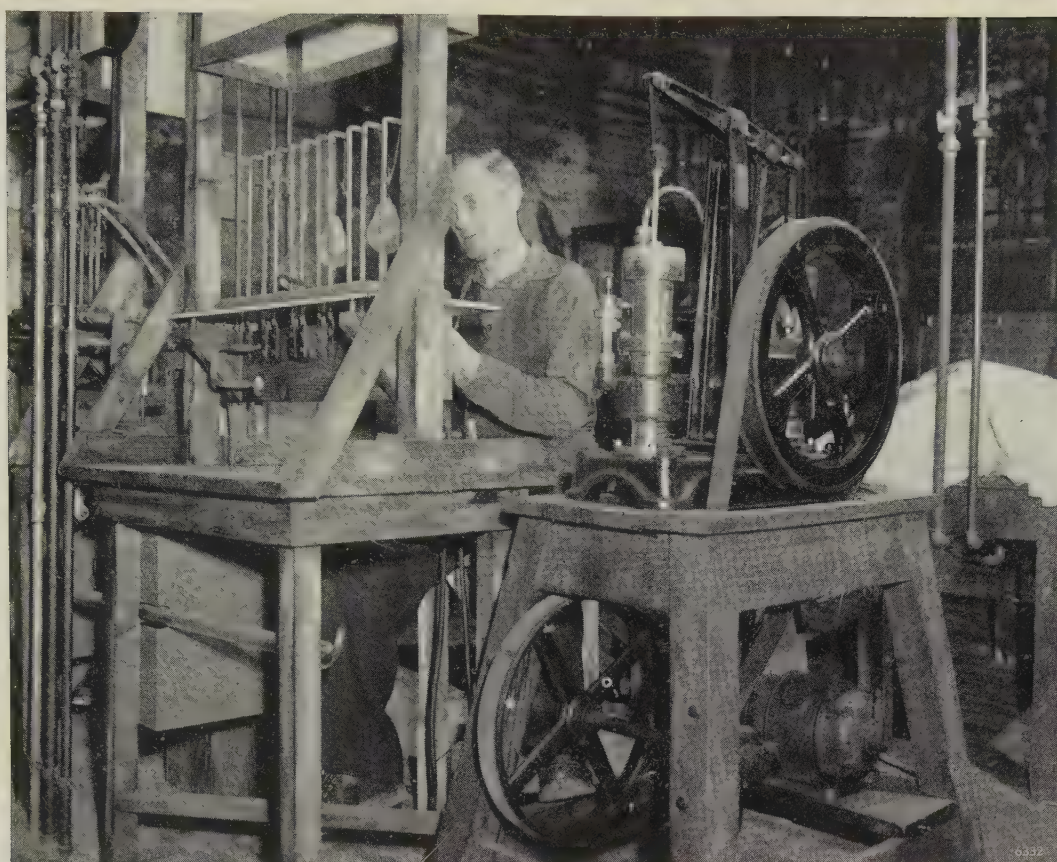


Fig. 8. Reconstruction of a pumping system for carbon-filament lamps, as must have been used by Gerard Philips when he first started up the factory. This reconstruction was made in 1951 on the occasion of the 60th anniversary of the Company, and the system was then in use for several weeks.

Plaster of Paris remained necessary for fixing the vitrite lamp caps to the bulb, and Gerard made enquiries amongst suppliers for special types of plaster, which had to be very hard and not to expand too much, otherwise the neck of the bulbs might be damaged (*letter X*).

An order placed on 3rd October 1891 with a printer at Krefeld for about 150 000 gummed and perforated labels of 15 × 10 mm, which were to be stuck on the lamps, was based on an estimate of the kinds of lamps and voltages for which there might be a demand. The order comprised:

17 500 labels for lamps of 8 candle-power
32 000 labels for lamps of 10 candle-power
70 000 labels for lamps of 16 candle-power
17 500 labels for lamps of 32 candle-power
17 500 labels for lamps of 50 candle-power.

The distribution according to voltage was as follows:

22 500 labels for 100 V
22 500 labels for 105 V
19 500 labels for 110 V
9000 labels for each of the voltages 65-98-102-108-112-115-120-125 V
4500 labels for each of the voltages 50-60-70-75 V.

The work of equipping the factory, making the pumps and various rather primitive aids to production, took almost a year. A fire insurance specification dated 5th February 1892 gives a clear picture of the inventory; see *letter XI*. The value of the buildings was assessed at 16 000 guilders (without foundations and "steam chimney" which were apparently not covered by insurance), and the machinery and equipment at about 25 000 guilders.

The early years of production

The first consignment of lamps (one hundred) was dispatched in May 1892. Remarkably enough, these lamps went to the stearin-candle factory at Gouda, a competitor in the lighting business which, notwithstanding all the improvements since made to electric lamps, has by no means had to quit the field. The fire hazard in the candle factory was the reason for the early change-over from gas lighting with open flames to safe lighting with electric lamps.

Other customers at that time were mainly steamship companies, theatres, restaurants and hotels, and shops selling luxury goods.

Letter XI (letter-book p. 401).
(Translated from the original Dutch.)

5th February 1892

Insurance specification for the lamp factory of Messrs. Philips & Co., Eindhoven.

Factory, office and adjoining buildings, excluding foundations and steam chimney	F. 16.000.00
Boiler, steam engine and steam pipes	F. 6.000.00
Machinery comprising: 3 dynamos with regulator, 1 bellows, 1 mechanical iron lathe with accessories, 1 automatic air-pump, 1 vacuum tank	F. 4.000.00
Mechanical instruments, apparatus, glass-blowing, forging and other tools, work benches, glass-blowers benches, woodwork, cupboards and factory equipment	F. 10.000.00
Office equipment including: one Chadwood safe, and office requisites and stationery . .	F. 600.00
Stocks including: platinum, mercury, glassware, brass mantles, chemicals required for lamp production	F. 5.000.00
	F. 41.600.00

The sales in 1892 were no more than 11 000 lamps. That was far too low. The plans for the factory were based on the estimate that an annual production of 150 000 lamps (500 daily) would be just sufficient to defray costs, and that a target of 1000 lamps daily should be aimed at to run the factory at a profit.

The Dutch market was too small, and competition on the international market was fierce (the A.E.G. in 1891 was already producing more than 3000 lamps a day, the Edison General Electric Company about 8000 lamps a day) and prices were dropping. Hopes of introducing the electric lamp for domestic lighting — which was to be the foundation of mass production — seemed to be dashed by the spectacular development of gas lighting. In 1885 Auer von Welsbach had patented his incandescent gas mantle, and its subsequent improvement raised the luminous intensity of gas burners from 16 candle-power to 70 or 80 candle-power, resulting in an increase in "luminous efficiency" from 0.09 to 0.65 candle-hours per litre of gas. Wherever there was a gas mains the number of consumers in the early 'nineties went up in leaps and bounds, and the reddish-yellow light from the carbon filament lamp contrasted miserably with the brilliant white, slightly greenish, gas light.

Added to all this were the early difficulties that Gerard experienced in running his factory. He had to be buyer and salesman as well as head of production, and after dismissing some of his employees who had proved unequal to their task he was obliged to shoulder an increasing variety of responsibilities himself. There was indeed a wide gulf between the work of an engineer, as he had imagined it, and that of a manufacturer. His knowledge of electrical engineering could only be applied sporadically. The purity of the raw materials and the proper operation of the Sprengel vacuum pumps (mercury-drop types) caused him the most trouble. All-round technician that Gerard was, he grappled competently with the numerous problems of production and was constantly introducing improvements: he replaced zinc-chloride cellulose as the conventional basic material for the carbon filaments by collodion acetate, which could be better controlled, and the mercury pump by the faster and more reliable oil-diffusion pump. But Gerard had his hands full with such technical problems, and could not pay sufficient attention to the selling side of the business. Sales remained far too low.

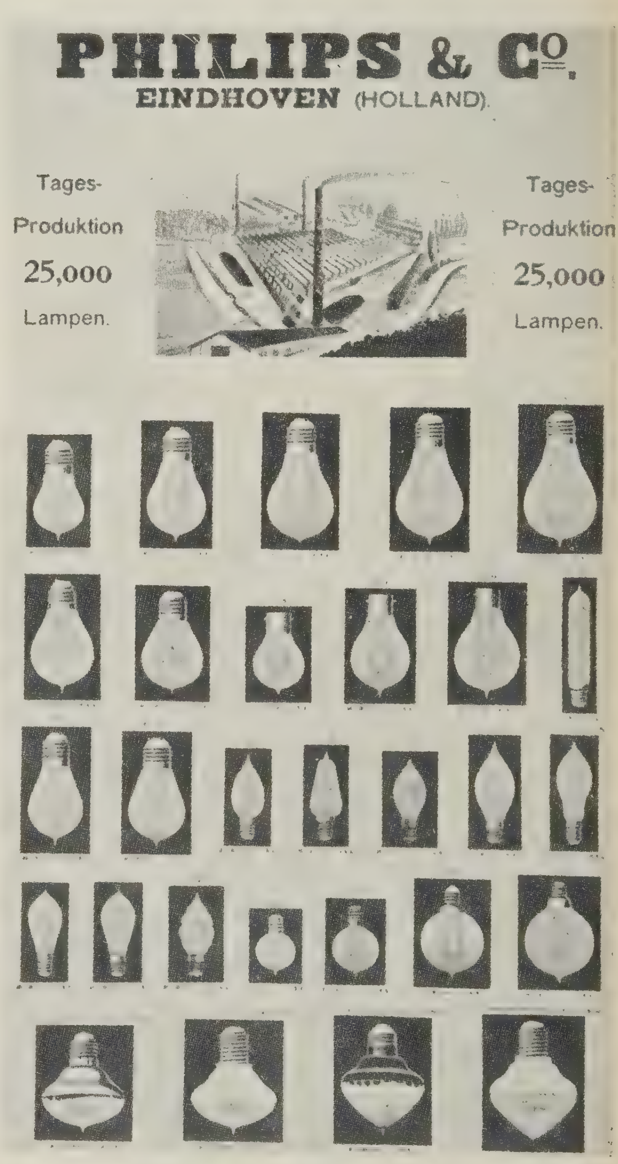


Fig. 9. Advertising poster of Philips & Co. in about 1903.

Fig. 10. A modern lamp factory: hall with a number of production groups parallel to each other, in the Philips lamp works at Weert (Netherlands), opened in 1961. Each production group covers the whole width of the hall and constitutes an independent unit. Each group, which is operated by three or four persons, is supplied with tungsten filaments, support rods, bulbs, lamp caps etc., and delivers a continuous stream of finished incandescent lamps (more than 2000 per hour). Here too the lamps of each production unit are subjected to the necessary inspection. The stream of lamps coming from each unit is carried on a conveyor belt through the floor to the packing machines under the hall.

Consequently, in 1894 father and son reached the painful decision to sell the factory and wind up the business. Once again a project to which Gerard had devoted all his energy was to come to nought. Would he now, at the age of 36, have to start afresh elsewhere? What had become of the independence he had set his heart on?

Actually it was a trifle that turned the tide at the critical moment. Someone who wanted to buy the factory tried to beat down the moderate asking price of 25 000 guilders by a further 1000 guilders, and that so irritated Gerard's father that he broke off negotiations and decided to risk another attempt at putting the enterprise on its feet. His confidence in his son's technical capabilities was unshaken, but he saw clearly where the shoe pinched: Gerard had to be relieved of the commercial work. When it proved difficult to find a suitable man for the job, it occurred to Gerard's father to offer it to his younger son, Anton Frederik.

Young Anton, till then engaged in a London banking house, entered his elder brother's small business in the beginning of 1895, at the age of 21. So quickly did he boost sales, largely by travelling to countries abroad — including Russia, where there were as yet few gas-works — that at the end of the same year Philips & Co. were no longer operating at a loss [5]).

In the following years production went from strength to strength:

1895:	100 000 lamps
1896:	280 000 ,,
1897:	630 000 ,,
1898:	1 200 000 ,,
1900:	2 700 000 ,,
1902:	3 600 000 ,,

The firm hold which Philips & Co. had managed by 1902 to acquire even in Germany, in spite of powerful German competition, is illustrated by the fact that the Düsseldorf Gewerbeausstellung (Industrial Exhibition) of that year was lit entirely by Philips lamps.

5) It is perhaps interesting to mention that the first electric lamp factory to go into regular production — originally 1000 lamps daily — founded by Edison in 1881, was also run at a loss for the first three years.

Even before the advent of the metal filament (the tungsten lamp entered the field in 1906) the factory had to be considerably expanded, a variety of special lamp types were developed, and production rose to 25 000 and more lamps daily (*fig. 9*). Meanwhile the production process was being increasingly mechanized and made more efficient. From the moment that Anton Philips took over the commercial side, Gerard Philips was able to give full expression to his technical talents as manufacturer and designer — he was after all a trained mechanical engineer — and mechanization claimed his undivided attention. When Gerard retired from the management in 1922 the production process was so highly mechanized that the output per man-hour was fifty times greater than in 1892.

It is outside the scope of this article to describe this and the subsequent progress up to the present day. Let it suffice to indicate the point it has now reached by an illustration (*fig. 10*): a recently opened factory turning out more than 2000 lamps an hour per production unit.

Our last figure (*fig. 11*) brings us back to the beginning of our story: it is a bas-relief showing the founder Gerard Philips, which has been built into the foot of the chimney of the (still existent) little factory of 1891.

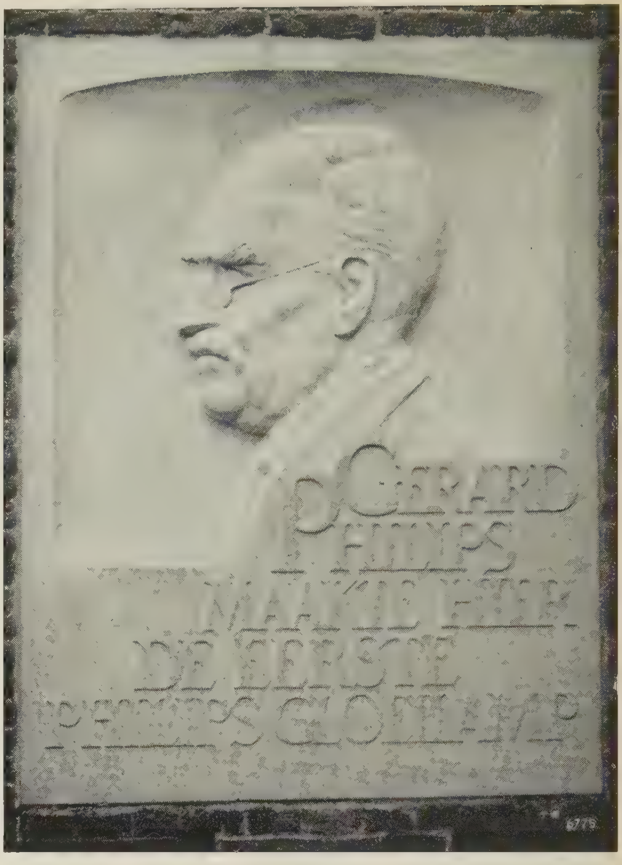


Fig. 11. Commemorative plaque affixed to the factory of 1891: "Gerard Philips made the first Philips incandescent lamp here".

Short bibliography

Anon. (under the pseudonym "Electron"), De Bougie Jablochkoff, Electrische Verlichting, published by Van Es, Amsterdam 1878 (in Dutch).

This booklet acclaims the demonstration at Paris of "a new form of lighting which has entered into its infancy", and aptly illustrates the topicality which the "distribution of the electric light" then possessed.

J. Dredge (Ed.), Electric Illumination, 1882 (Part I) and 1885 (Part II).

Mainly contributions compiled from "Engineering" with extracts from patents granted in America and England.

A. von Urbanitzky, Electricity in the service of man (adapted from the German by R. Wormell), Woodall, London 1886.

Idem, Die elektrische Beleuchtung und ihre Anwendung in der Praxis, 2nd Edn., Hartleben, Vienna 1890.

G. S. Ram, The incandescent lamp and its manufacture, The Electrician Publ. Comp., London 1893.

The author describes his experience of many years in the making of lamps, presenting his knowledge "with as little mathematical embellishment as, under the circumstances, is possible".

H. Weber, Die elektrischen Kohlenglühfadenlampen, ihre Herstellung und Prüfung, Jänecke, Hannover 1908.

This book contains among other things a useful historical review. Also of interest is a chapter on the repair of electric lamps, i.e. the removal of carbon deposits or the replacement of a burnt-out filament. The author is opposed to this practice and remarks: "The user will, if the lamp comes up to reasonable expectations, gladly buy a new lamp at an appropriate price after the old one has become defective, and will not want to have cheaper repaired lamps".

A chronological history of electrical development, Nat. Electr. Manuf. Assoc., New York 1946.

F. A. Lewis, The incandescent light; a review of its invention and application, The Thomas Alva Edison Foundation, West Orange (N.J.) 1949.

G. F. Westcott, Mechanical and electrical engineering (Classified lists of historical events, The Science Museum), H. M. Stat. Off., London 1955.

P. J. Bouman, Anton Philips of Eindhoven, Weidenfeld and Nicolson, London 1958.

Summary. A brief account is given of the early period of electrical engineering, and a picture is presented of the situation that existed in the field of lighting in Europe, and particularly in the Netherlands, when Gerard Philips started manufacturing lamps at Eindhoven. A valuable source of historical data concerning the creation of the factory was found in a letter-book containing copies of the correspondence addressed by Gerard Philips to numerous persons between April 1889 and April 1892. Eleven of these letters, which contain interesting details of that period, are printed here *in extenso*.

IODINE INCANDESCENT LAMPS

I. PRINCIPLE

by J. W. van TIJEN *).

621.326.79

A short time ago a new type of incandescent lamp possessing very attractive properties was introduced. The lamp owes these properties to the presence of a small quantity of iodine inside the bulb, hence the name "iodine lamp" by which it is generally known.

The value of this invention can best be made clear against the historical background of the incandescent lamp, with special references to the gradual improvement of luminous efficiencies. In an incandescent lamp electrical energy is converted into light by heating a filament to incandescence by the passage of an electric current. The higher the temperature of the filament the more efficient is the energy conversion (greater luminous efficiency), but the faster too, unfortunately, is the rate at which the filament material evaporates. Only if the rate of evaporation can be reduced is it possible to raise the temperature without at the same time shortening the life of the filament.

The improvement in the luminous efficiency of the incandescent lamp that has been achieved in the eight decades of its existence may therefore be described as the result of constant efforts to overcome filament evaporation. The iodine filling is the latest tool for this purpose.

Short history of the incandescent lamp [1])

The incandescent lamp made by Edison in 1879 consisted of a carbon filament mounted in an evacuated glass bulb. This type of lamp (rated for about 50 W) had a luminous efficiency in the region of 3 lumens per watt [2]).

Subsequent developments were dominated at first by the search for filament materials less subject to evaporation than carbon. Following Nernst's ceramic filament and the use of osmium and tantalum, the drawn tungsten filament was introduced (by Coolidge) in 1910. Using this filament, also mounted in an evacuated bulb, luminous efficiencies of about 9 lm/W were achieved with a consumption of 40 W. This improvement by a factor of 3 compared with a carbon-filament lamp was chiefly the result of being able to raise the filament temperature from about 2100 °K to 2400 °K. (Another reason for the improvement was that the spectral energy distribution of the radiation emitted by tungsten is more favourable than from carbon at the same temperature, in that the visible radiation from tungsten constitutes a larger percentage of the total power dissipated by radiation.)

Since then no better material than tungsten has been found. All subsequent developments have therefore been based on the tungsten filament, efforts being concentrated on minimizing its rate of evaporation. Langmuir took this development a good step forward by filling the bulb with inert gases, such as argon and nitrogen (1913). This had the effect of returning to the filament a certain percentage of the evaporated tungsten by the collision of tungsten atoms with the gas molecules, enabling the temperature of the filament to be raised to about 2800 °K while maintaining the same useful life. The gas filling has the drawback, however, that energy is lost by heat transfer to the gas. Langmuir reduced these "gas losses" by coiling the filament, thereby achieving a luminous efficiency of 11 lm/W from a 60 W lamp with a gas filling of about one atmosphere. In the 'thirties this was raised to 12 lm/W by introducing a double coil (the coiled-coil filament), which reduced the gas losses still further.

Efficiency was again improved by using instead of the conventional argon an inert gas of greater molecular weight, such as krypton or xenon. The greater molecular weight has the effect of reducing the tungsten evaporation and also the heat transfer to the gas. Krypton and xenon are relatively scarce and therefore more expensive, for which reason they are used only in special lamps where they are economically justified.

For a long time it looked as if the evolution of the incandescent lamp's efficiency had come to a standstill, until in 1959 the iodine filling was introduced. It was found possible by means of a chemical process involving iodine to return to the filament that part of the evaporated tungsten which is not returned by

*) Philips Lighting Division, Eindhoven.

[1]) For a comprehensive history of the incandescent electric lamp see: A. A. Bright Jr., The electric-lamp industry, MacMillan, New York 1949. See also the article by N. A. Halbertsma in this number (p. 222) and further W. Geiss, Philips tech. Rev. **1**, 97, 1936 and **6**, 334, 1941.

[2]) The theoretical maximum for white light (equi-energy spectrum) is approximately 220 lumens per watt.

the filling gas and which settles on the bulb wall.

In the following an attempt will be made to give some idea of the chemical and physical effects that occur in an iodine lamp.

The regenerative iodine cycle

The principle underlying the iodine lamp is a regenerative cycle whereby the tungsten deposited on the bulb wall is converted at the temperature of the wall into a volatile compound, which then decomposes on or in the neighbourhood of the filament. This kills two birds with one stone:

a) it prevents blackening of the bulb wall;

b) the tungsten filament suffers no weight loss.

Various tungsten compounds enter into consideration for such a cycle. The halides and the carbonyl compound $W(CO)_6$ have the necessary volatility. As regards the other properties required, the halides are more suitable than the carbonyl compound, since the decomposition temperature of the latter is rather low. Moreover its use involves the risk of tungsten-carbide formation, which might cause brittle spots to appear in the filament.

The fundamental idea of a regenerative halogen cycle is fairly old. As long ago as 1916, Hamburger published particulars of an imperfect cycle produced with the aid of chlorine, on the basis of experiments done in our research laboratories [3]). It was not until 1959, however, that Zubler and Mosby in the General Electric laboratory at Cleveland succeeded in making technically useful lamps on this principle, using a regenerative iodine cycle [4]). One of the difficulties they had to overcome was to produce bulbs capable of withstanding higher temperatures than those found in normal incandescent lamps (see also p. 240).

We shall now consider the various tungsten halides in more detail. Their formation and decomposition takes place according to the following type of reaction:

$$W + nX \rightleftarrows WX_n,$$

where X represents a halogen atom and n is a small integer. The situation of the equilibrium depends strongly on temperature, as we shall show with the aid of the graph in *fig. 1*. The position of the equilibrium is given by the equation

$$\frac{P_W\,(P_X)^n}{P_{WX_n}} = K,$$

where P_W, P_X and P_{WX_n} are the partial pressures of the components in equilibrium, and K is the equilibrium constant. In fig. 1 the logarithm of the calculated equilibrium constant K is plotted as a function of temperature. At values of $K \ll 1$ the partial pressure of the atoms W and X is much higher than that of the molecules WX_n; at values of $K \gg 1$ it is much lower. At about the temperature where the K line passes the value 1 (or $\log K = 0$) the equilibrium changes over from one side to the other.

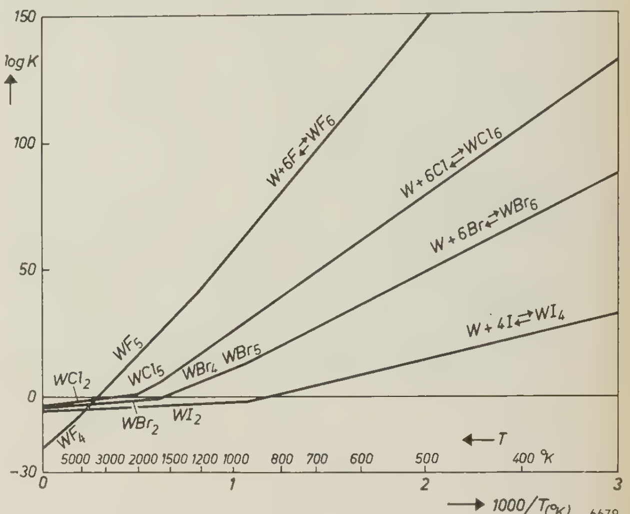


Fig. 1. The thermodynamically calculated equilibrium constant K for the formation of all tungsten halides, as a function of temperature T. The graph shows that, at the usual bulb-wall temperatures (200-600 °C) the equilibrium lies on the side of the compound, and at the usual filament temperatures (3000 °K) on the side of the constituent elements. These are the necessary conditions for a regenerative tungsten cycle.

Fig. 1 shows that at the high temperature at which tungsten filaments are incandescent (approx. 3000 °K) most tungsten halides will be almost completely dissociated. A possible exception is the fluoride, which will only be partly dissociated at the temperature in question. In the case of the chloride the temperature of the equilibrium cross-over lies at about 2000 °K, for the bromide at about 1500 °K and for the iodide at about 1000 °K.

From the above data we may conclude that:

1) at conventional filament temperatures all tungsten halides are dissociated to the extent required for the regenerative cycle;

2) at all normal bulb-wall temperatures (200-600 °C) the equilibrium lies at the tungsten-halide side, which is also a necessary condition for the regenerative cycle.

[3]) L. Hamburger, Chem. Weekbl. **13**, 535, 1916.

[4]) E. G. Zubler and F. A. Mosby, Illum. Engng **54**, 734, 1959.

We have been considering only the reaction with halogen *atoms* and not that with molecules. The reason is that, at the high temperature of the filament, all halogen molecules dissociate completely into atoms. Although these atoms diffuse to regions of lower temperature, they have little chance to associate there owing to the low probability of collision at the gas pressures chosen in practice. Moreover, the reactivity of the halogen atoms is many times greater than that of the halogen molecules. The formation of tungsten halides will therefore be primarily due to reaction with atoms.

It appears from the foregoing that, in principle, all tungsten halides are suitable for use in incandescent lamps. Nevertheless, it is not by chance that the iodine cycle has had the most success. One of the main reasons is the fact that in a regenerative cycle the aim must be to attack the tungsten deposits on the relatively cold bulb wall while leaving the relatively cold ends of the tungsten filament intact. It can be seen from the graph that the filament ends are least subject to attack when iodine is used. In that case the temperature of the filament ends need be no higher than about 1500 °K to remove the danger of chemical attack. It is not difficult to find practical constructions that fulfil this requirement.

Whilst this may seem to open the way to the making of lamps of higher than normal efficiency, or possibly of longer life, further consideration shows that there are other conditions that must also be satisfied.

Analysis of the reasons for the limited life of normal incandescent lamps and iodine lamps

For a proper understanding of the phenomena in an iodine lamp, we shall take a closer look at the process by which the filament deteriorates in operation and finally burns out. Let us first consider a vacuum lamp. If the filament in such a lamp had a perfectly constant diameter and underwent completely uniform evaporation, the filament, growing steadily thinner, would pass less and less current and become steadily colder. The result would be an infinitely long filament life and a steadily declining light output. The actual finite life of the filament is due to the occurrence of thin or weak spots which are loaded with the full current. At these spots the tungsten wire gets very hot and finally breaks.

This is a random process but there is nevertheless a fixed and entirely reproducible relation between the rate of evaporation and the life of a filament. To illustrate this, *Table I* presents data [5]) relating to uncoiled tungsten wire in vacuo, together with the appertaining luminous efficiencies.

[5]) C. Zwikker, Physica **5**, 252, 1925.

Table I. The life of an uncoiled tungsten filament in vacuo.

Temperature °K	Luminous efficiency lm/W	Rate of evaporation v g/cm² s	Life H of wire of 0.01 mm diameter hours	$v \times H$
2000	2.93	15.5×10^{-15}	1.04×10^{7}	16.1×10^{-8}
2200	5.71	22.4×10^{-13}	7.20×10^{4}	16.1×10^{-8}
2400	9.77	13.8×10^{-11}	1.17×10^{3}	16.1×10^{-8}
2600	14.8	41.7×10^{-10}	3.86×10^{1}	16.1×10^{-8}
2800	20.9	83.3×10^{-9}	1.9	15.8×10^{-8}
3000	27.8	10.5×10^{-7}	0.15	15.7×10^{-8}

Apart from the very rapid decline in life with increasing temperature, we notice especially that the life is almost exactly inversely proportional to the rate of evaporation. This means that the filament will nearly always burn out as soon as a particular constant percentage of tungsten has evaporated. This percentage is known as the end-of-life weight loss, and for vacuum lamps it is 10 to 15% of the weight of the wire.

In a gas-filled lamp the situation is very much the same. The only difference is that, owing to the tungsten atoms constantly evaporating and returning to the filament, making the wire more and more irregular, the end-of-life weight loss is smaller by a factor of 2 or 3 than in vacuum lamps. This effect, which in itself would impair the life of the filament, is more than compensated by the retarding effect of the gas filling which, at a pressure of about 1 atm, may easily slow down the rate of evaporation by a factor of 50.

What now is the situation in an iodine lamp? When the lamp is burning the tungsten evaporates in the normal way, part of the evaporated tungsten being reflected back to the filament by the gas molecules. The part not so reflected reaches the bulb wall, where it reacts with the iodine vapour and is converted into volatile tungsten iodide; this dissociates near the filament, as a result of the high temperatures prevailing there, and thus reinforces the local concentration of tungsten vapour. This in turn increases the deposition of tungsten on the filament, until just as much tungsten is deposited on the filament as the latter loses by evaporation.

In the ideal case of uniform tungsten evaporation and deposition, this would mean that the iodine lamp would have an infinitely long life and a constant light output (unlike the "ideal" vacuum lamp, whose light output would gradually decline). This ideal case is never found, for there will always be temperature differences in the incandescent filament. We shall see below what consequences this has.

Owing to diffusion, the tungsten vapour around the filament shows a homogeneous distribution. The concentration of the tungsten vapour is adjusted, as it were, to the *average* temperature of the filament. On the relatively hot spots of the tungsten surface more tungsten will evaporate than will be deposited; conversely, on the relatively cold spots more will be deposited than evaporated.

Thus, although the filament, seen as a whole, suffers no weight loss in an iodine lamp, tungsten can certainly "migrate" from relatively hot parts of the filament to relatively cold parts. This process can in fact be observed, and its effect is that the relatively hot spots become gradually thinner and hotter until finally the filament burns out.

If, by analogy with the behaviour of normal incandescent lamps, we may reckon with a more or less constant "end-of-life migration", we can show that the following formula [6]) holds for the life H of an iodine lamp:

$$H \propto \frac{T_{\mathrm{h}}^{-32}}{\Delta T},$$

where ΔT is the temperature difference between relatively hot and cold parts of the filament and T_{h} is the temperature of the hottest part.

For $\Delta T = 0$ the life of the filament would be infinitely long. This ideal, as we have said, cannot be achieved because small irregularities are always present or develop in a tungsten filament. Again, for a given temperature difference the life decreases very rapidly with increasing T_{h}, because the tungsten migration process is greatly accelerated at higher temperatures.

Compared with the tungsten evaporation in normal incandescent lamps, however, tungsten migration is a slow process provided that special precautions are taken in the construction and filling of the iodine lamp (see points (5) and (6) in the following section). In fact, therefore, the iodine lamp offers a longer life and/or a higher efficiency than a normal incandescent lamp. For the same life some types of lamp, filled at a pressure of about 1 atm, show an improvement in efficiency of about 25%. Another advantage of the iodine lamp is that its light output remains constant throughout life (there being no blackening of the wall and no weight loss in the filament).

[6]) This formula, which we derived with the aid of the kinetic gas theory, applies to the temperature range from about 2700 to about 2900 °K. Outside this range the formula holds with an exponent of T_{h} differing somewhat from that used here. The reliability of the formula has been confirmed by numerous experiments.

Some technical details of the iodine lamp

To sustain an iodine cycle in an incandescent lamp, the lamp must meet certain requirements which cause it to differ in construction from normal incandescent lamps.

1) Size and temperature of the bulb.

The bulb of a normal incandescent lamp should preferably not be too small, as otherwise the blackening that occurs will absorb too much light, and, more especially, the bulb will get too hot.

In the case of the iodine lamp the situation is different; for one thing there is no blackening, and for another the bulb temperature *must* be higher than normal. At too low temperatures the rate of formation of tungsten iodide would be too low, and moreover the compound would condense. The dimensions of the bulb are often chosen so as to obtain a bulb temperature of about 600 °C. This means that the bulb must be made of quartz glass or some other type of glass having a high softening point.

2) Lamp shape.

Iodine lamps are made in a variety of shapes. In the case of high-wattage iodine lamps (from 500 W) the most usual shape so far is a cylindrical bulb with a coiled filament along the axis (see *fig. 2*).

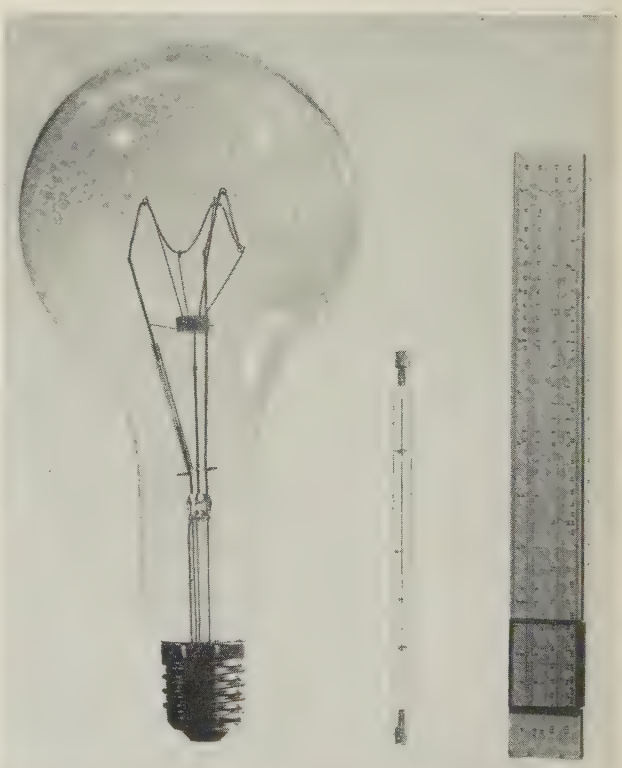


Fig. 2. A 1000 W iodine lamp, with a 1000 W incandescent lamp of normal construction for comparison.

A tubular lamp of this kind, whose length is large compared to its diameter, must be operated horizontally, otherwise the iodine will accumulate by thermal diffusion at the bottom of the bulb and the cycle will no longer be maintained.

3) Iodine content.

The lamps are filled with an inert gas to which about 0.25×10^{-6} moles/cc of iodine is added. Too much iodine causes loss of light as a result of absorption by the iodine vapour; too little iodine makes the iodine cycle too slow.

4) Mounting and support of the filament.

The usual materials, such as nickel, molybdenum, tantalum and iron, are not suitable for the filament supports, unless measures are taken to prevent them from reacting with the iodine. The metals must therefore either be given a protective coating, e.g. glazed, or noble metals like platinum must be used, or special alloys. Tungsten can also be employed, but the components must then be designed so as to ensure that they reach a sufficiently high temperature (see also p. 239).

5) Purity of the gas filling.

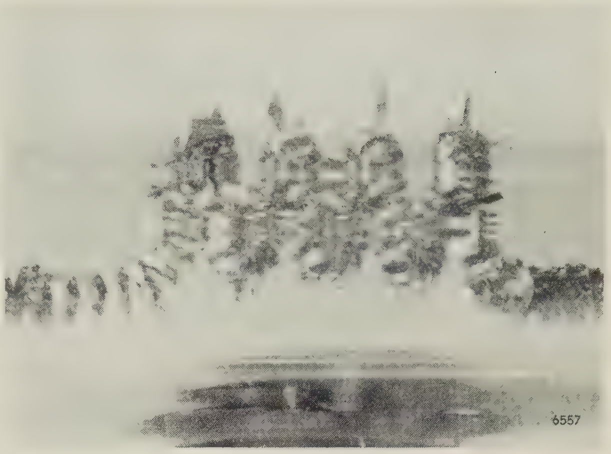
It is a known fact that traces of water vapour in an incandescent lamp rapidly transport tungsten by a cyclic process from the filament to the bulb wall. Although in an iodine lamp the tungsten deposited on the bulb wall is returned to the filament by the iodine cycle, this additional transport of tungsten leads to very irregular deposition on the filament (see *fig. 3*), resulting in a relatively short life. Other impurities can also have an adverse effect on the life of the lamp. In the manufacture of iodine lamps, therefore, measures are necessary to ensure that the gas filling has a high degree of purity.

6) Reduction of temperature gradients along the filament.

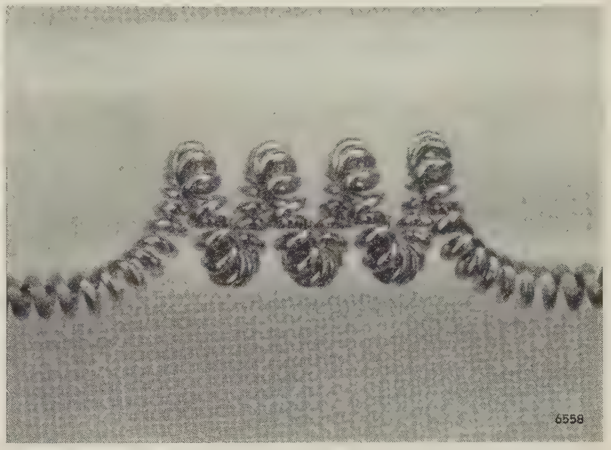
Since tungsten has the tendency to migrate from relatively hot to relatively cold spots, steps must be taken to reduce the temperature gradients along the filament. For example, the components used for mounting and supporting the filament should be as light as possible in construction, so as to minimize the loss of heat through them.

Further improvement of efficiency by increased filling pressure

Since iodine lamps, as we have seen, are relatively small, they can readily be filled with gases at pres-



a



b

Fig. 3. *a*) Tungsten filament of an iodine lamp in which traces of water vapour were present, *b*) tungsten filament of an iodine lamp containing no water vapour. Both lamps had burnt for the same number of hours.

sures higher than one atmosphere. The small bulbs are relatively strong and easily capable of withstanding a higher pressure. Under favourable conditions, filling pressures up to about 10 atm are feasible in very small bulbs.

A high-pressure filling in iodine lamps is particularly advantageous in view of the virtual absence of convection currents in the small bulbs. In standard gas-filled incandescent lamps, where these currents do occur, a higher pressure is a double-edged weapon: on the one hand it slows down the evaporation of tungsten, on the other it increases the heat loss via the gas. The latter, however, is entirely due to convection. In a "stationary" gas the thermal conduction is independent of pressure. All we are left with in small iodine lamps, therefore, is the retarding effect on filament evaporation. According to a formula calculated by us and confirmed by experiment, the luminous efficiency in

that case is proportional to the filling pressure to the power 0.12. With higher pressures up to about 10 atm, which can be used under appropriate conditions, luminous efficiencies can thus be achieved which are about 30% higher than in corresponding iodine lamps filled at a pressure of 1 atm [7]).

[7]) About half the efficiency improvement of 25% at a filling pressure of 1 atm, mentioned on p. 240, is estimated to be due to the increase of pressure that takes place when the lamp is burning.

To sum up, it can be said that the iodine lamp compares favourably with the normal incandescent lamp by maintaining full lumen output throughout life. A few types of iodine lamp, having a "normal" life, offer efficiency gains up to 25%. This applies to lamps filled at a pressure of 1 atm. In those types where very high pressures are technically feasible, a further improvement of up to 30% can be achieved, which represents a gain in efficiency of 60% over normal incandescent lamps.

IODINE INCANDESCENT LAMPS

II. POSSIBLE APPLICATIONS

by J. J. BALDER *).

621.326.79

The iodine lamp is usually cylindrical in shape, with a diameter of about 10 mm, and has a coiled filament mounted along the axis of the bulb. We shall discuss first some possible applications of iodine lamps for wattages higher than 500 W, which are long in proportion to their diameter, and then those of relatively short iodine lamps of lower wattage [1]).

The first category of lamps is particularly suited for use in conjunction with cylindrical reflectors. The beam of light from this combination of lamp and reflector can fairly easily be given the desired form in the plane perpendicular to the long axis, the light distribution in this plane being controlled by the shape of the reflector cross-section. If necessary, a beam-spreading lens may be added in front of the reflector.

Effective control of the light in planes through the axis is more difficult. If nothing is done to prevent it, the beam in such axial planes fans out over the whole 180°. The width of the beam in those planes can only be limited to some extent by using specially shaped end mirrors or other more complicated devices.

The obvious applications are therefore to be found where a beam is wanted which is broad in one direction and narrow in the direction perpendicular thereto. Beams of this kind are required for flood-lighting, the lighting of sports fields and similar flat areas, poster lighting etc. Other possible applications are the lighting of factories, churches, shopping arcades, warehouses, theatres, studios and so on. To function properly the lamps must be operated horizontally (see Part I of this article). In nearly all the cases mentioned, the horizontal position of the lamp is not in conflict with the use for which the lighting is intended.

The small transverse dimensions of the lamp make it possible to obtain the required beams with good optical efficiency using fairly small reflectors, provided the materials and the design of the fittings are well chosen with a view to the possibility of high temperatures. *Fig. 1* shows a fitting for a 1000 W iodine lamp, suitable for sports-field lighting, for example, or for flood-lighting.

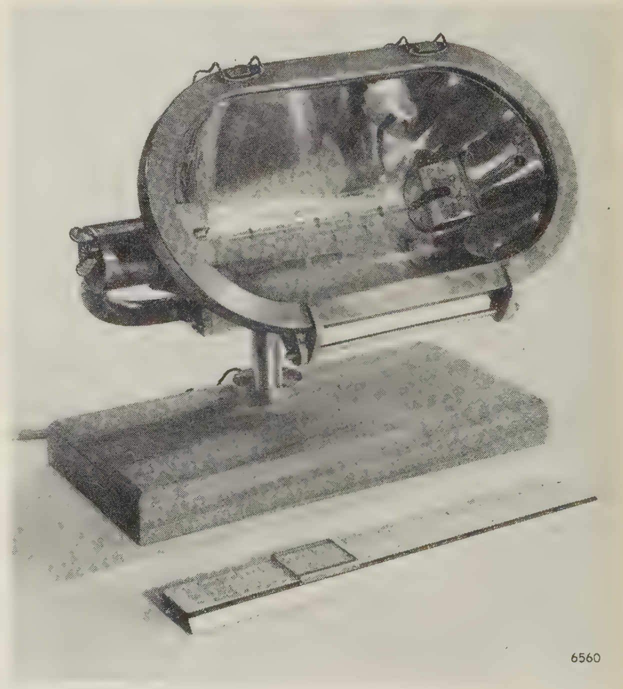


Fig. 1. A 1000 W iodine-lamp fitting, suitable for sports-field lighting for or flood-lighting.

*) Philips Lighting Division, Eindhoven.

[1]) For potential applications of the iodine lamp in general, see also C. J. Allen and R. L. Paugh, Illum. Engng **54**, 741, 1959.

In regard to the applications of the low-wattage category of lamps (up to a few hundred watt), the filament of which may be from a few millimetres to a few centimetres in length, long cylindrical reflectors need no longer be considered. More or less bowl-shaped, possibly faceted, reflectors are suitable for some purposes; where the filaments are

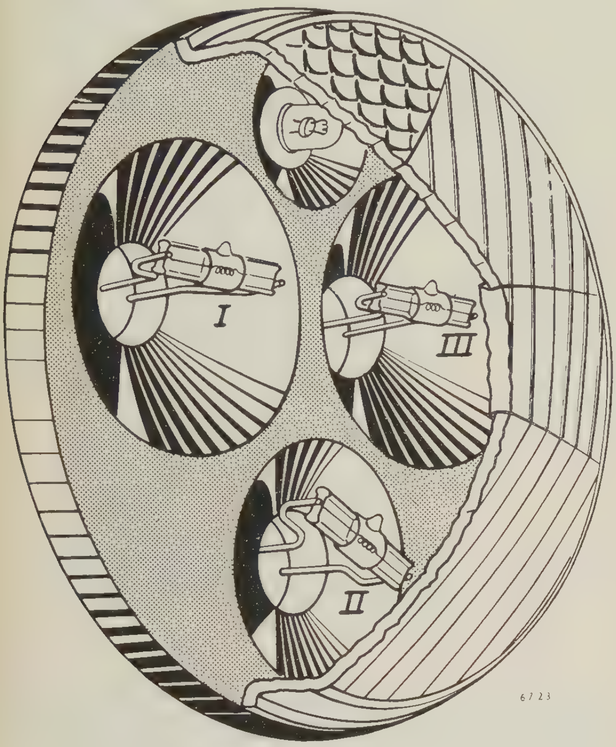


Fig. 2. Example of a car headlamp fitted with three 35 W iodine lamps, *I*, *II* and *III*. The individual reflectors are paraboloids of revolution, with diameters of 75, 60 and 75 mm respectively. In this design the three reflectors are contained in a space equal in diameter to that of many normal headlamps (170 mm). The front glass consists of segments which each give a different beam spread. The dipped beam (passing beam) is obtained from lamps *I* and *II*, the main beam (driving beam) from lamps *I* and *III*. The small normal incandescent lamp fitted in a fourth, small reflector at the top functions together with the appertaining segment of the front glass as a side light.

only a few millimetres in length use may even be made of reflectors having rotational symmetry, with a parabolic or other, more complicated form of cross-section. Here, too, the smallness of the light source makes it possible to use small reflectors.

As an example of the application of low-wattage iodine lamps, we shall consider their use in car headlamps.

Car headlamps must be able to illuminate the road in two different ways: by a main beam (driving beam) and, in the presence of approaching traffic, by a dipped beam (passing beam). The passing beam can with advantage be made asymmetrical. Both forms of lighting have to comply with statutory requirements [2]). We shall now discuss one of the many possible designs of a car headlamp using iodine lamps. In this case three lamps of 35 W each are used; see *fig. 2*.

The three iodine lamps are contained in a space having the dimensions of a normal car headlamp measuring 170 mm across. Their common front glass consists of four segments, each producing a different beam spread. The first lamp (*I*) is mounted in a reflector 75 mm in diameter which, like the others, is a paraboloid of revolution. The light which it reflects is given a considerable spread by the segment of the front glass through which it passes. In this way a broad beam is obtained as shown in diagram *I* in *fig. 3*. The second iodine lamp (*II*) gives a concentrated beam as represented in diagram *II* in fig. 3, with the aid of a reflector only 60 mm in diameter and a segment of the front glass giving little spread. The third iodine lamp (*III*) is mounted like the first in a reflector 75 mm in diameter, but in this case the front glass gives a moderate spread. The resultant distribution can be seen in diagram *III*.

Beams *I* and *II* combined produce a good asymmetrical passing beam (see diagram *A*), and *I* and *III* together give a good main beam (see diagram *B*). When switching from passing to main beam and vice versa, lamp *I* continues to burn, thus ensuring a certain continuity in the lighting of the road.

We have not considered in this example such details as the positioning of the filament, the screening in directions where oncoming traffic might be troubled by glare etc. In these respects there is a choice from many possible designs. *Fig. 4* shows as an example a lamp intended for axial mounting of the filament in the reflector. There is also a much

Fig. 4. Example of an iodine car lamp (14 V, 70 W) designed for axial positioning of the filament in the reflector. For comparison, see the headlamp in fig. 2, where the filaments are perpendicular to the reflector axis.

[2]) See the introduction to the article by W. Bähler in this number (p. 278), and J. B. de Boer and D. Vermeulen, Philips tech. Rev. 12, 305-317, 1950/51.

wider choice than has been mentioned here in regard to wattage, the size of reflectors, the configuration and combination of reflectors, and hence of the composition, character and intensities of the beams. All car headlamps designed for operation with iodine lamps are superior to standard headlamps by reason of either a higher optical efficiency for the same size of headlamp, or a smaller size for the same optical efficiency, and also by reason of the better luminous efficiency of the iodine lamp itself.

Summary of I and II. The history of the incandescent lamp has been marked by continuous efforts to overcome filament evaporation, with the object of raising the luminous efficiency and/or lengthening the life of the lamp. A new tool for that purpose is the regenerative iodine cycle, achieved by adding a small quantity of iodine to the filling gas. The evaporated tungsten is deposited on the bulb wall and converted into a volatile iodide, which compound is again decomposed in the high-temperature region near the filament. In this way all the evaporated tungsten can be returned to the filament. The article describes the conditions for maintaining such a cycle, which in principle is also possible with other halides, and explains why the best results have been obtained with iodine. Iodine lamps are relatively small and have a higher bulb-wall temperature than normal incandescent lamps (about 600 °C). For this reason they are made of quartz glass or of other types of glass having a high softening point. Iodine lamps for high power ratings (500 W and more) are generally long and cylindrical in shape and are operated horizontally. Filled with inert gas at a higher pressure than the one atmosphere usual in normal incandescent lamps, they give an even higher luminous efficiency, owing to the absence of convection currents in the small bulbs; as a result there is scarcely any increase in the heat losses of the gas with increasing pressure. Under favourable conditions the resultant gain in efficiency compared with normal incandescent lamps is about 60%.

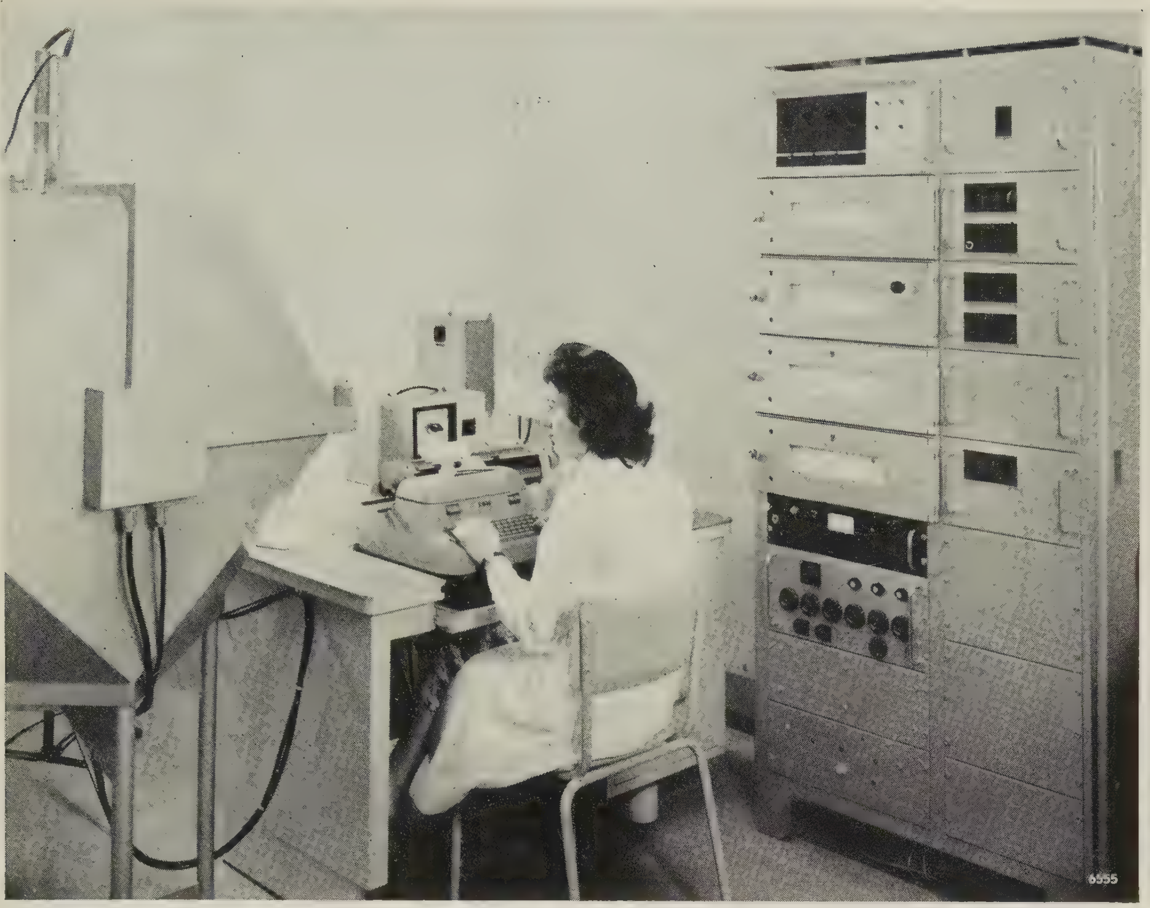
Article II discusses some possible applications of iodine lamps, in particular their use in car headlamps. An example is described in which the headlamp is fitted with three 35 W iodine lamps, each in its own small reflector.

AUTOMATIC DIGITAL PHOTOMETER FOR TESTING INCANDESCENT LAMPS

In an incandescent-lamp factory regular photometric measurements have to be made on large numbers of lamps by way of sample inspection. Done by conventional methods these measurements call for constant attention of a high order from the operator. After placing the lamp in the photometer she must accurately adjust the voltage on the lamp to the required value by means of a meter reading (and keep it at that value). She must then carefully read the luminous flux and the power consumption from two meters, enter the readings for each lamp without error in the inspection sheet, divide one value by the other to find the luminous efficiency (lumens per watt), divide this in turn into the luminous-efficiency figure specified for the particular type of lamp, and again record both results.

The equipment illustrated here, which is in use at Philips' new incandescent lamp factory at Weert (Netherlands), performs practically all these operations automatically. The operator has no meters to read, no calculations to perform and very little to record. She selects the voltage on a keyboard at her right on the table (not visible in the photo): there is a choice from 80 values between 90 and 287.5 V. An automatic control system keeps the lamp voltage at the selected value to within 0.1%. On the same keyboard she selects the luminous efficiency specified for the type of lamp under test and the appropriate (coupled) ranges on the watt and lumen meters (choice of six ranges). The selected values of voltage and specified luminous efficiency are automatically printed on the inspection sheet which the operator has inserted in the electric typewriter and on which, where necessary, she has typed a few identifying particulars of the type of lamp tested. After placing each lamp in the photometer (on the extreme left in the photograph) the operator presses a button. The system automatically allows the lamp to burn for a preset time, e.g. 10 seconds, sufficient for it to reach a steady state, after which the system automatically carries out the measurements, performs the calculations mentioned and prints out the results on the inspection sheet. The progress of these automatic operations is signalled by pilot lights on the keyboard.

The installation is composed of series-produced industrial equipment. The cabinet seen on the right contains in the left-hand part two automatic potentiometers for measuring the lumens and watts, one automatic potentiometer which acts as an analogue computer for the division operations, and — above — an analogue-digital converter, which



translates the continuously variable results of the measurements and calculations into the discontinuously variable signals required for driving the electric typewriter. A fourth automatic potentiometer works as a servo-system for the final adjustment of the lamp voltage (which thus takes only a few seconds). The standard of accuracy required makes it necessary to operate the lamps from a DC supply. The DC generator used (not shown in the photograph) is fed by a stabilized power pack, bottom left in the cabinet.

The right-hand part of the cabinet contains the programme switch and relays for controlling the automatic measuring and computing cycle, and all switches for adjusting the voltage, meter ranges and so on. The switches are operated by remote control from the above-mentioned push-buttons on the keyboard. Grouping them in one cabinet together with the appertaining meters made it possible to simplify the wiring. The equipment as a whole is checked twice a day by measurements on standard lamps.

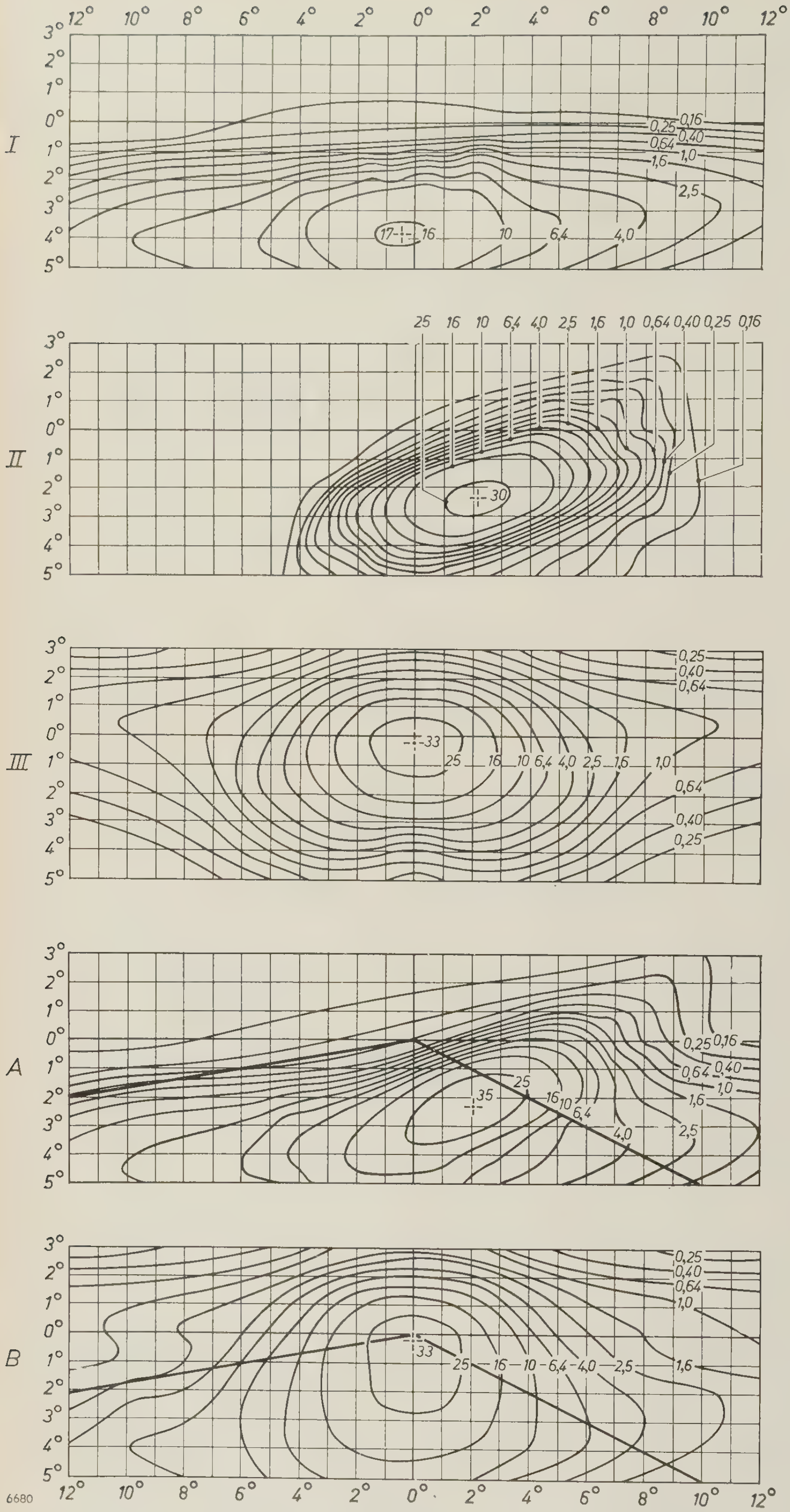


Fig. 3. Isocandela diagrams of the car headlight of fig. 2, measured at a distance of 25 metres. The figures on the contours give luminous intensities in kilocandela. Diagrams *I*, *II* and *III* relate to the iodine lamps *I*, *II* and *III* respectively. Diagram *A* represents the sum of the beams in diagrams *I* and *II*, which is a European asymmetrical passing beam. The diagram also shows the left-hand and right-hand kerbs of a road 6 metres wide as seen from a car headlamp situated at a height of 0.75 metres above the middle of the right-hand half of the road [2]). Diagram *B* gives the sum of the beams from diagrams *I* and *III*: this is the driving beam. Here too the sides of the road are indicated as in diagram *A*.

RECENT IMPROVEMENTS IN SODIUM LAMPS

by M. H. A. van de WEIJER *). 621.327.532

Introduction

The development of sodium lamps in recent years has led to marked improvements in their luminous efficiency and to a much smaller decline in luminous flux during the life of the lamp. Better thermal insulation largely accounts for the higher efficiency; the more constant light output has been achieved by making the discharge tube from a new kind of glass, which is less susceptible to attack by sodium, and by improving its design.

Until recently the only type of sodium lamp in common use had a detachable vacuum jacket (Dewar flask) for thermal insulation (see *fig. 1a* and *b*). An advantage of this construction is that the old vacuum jacket can be used again when it becomes necessary to replace the discharge tube.

*) Philips Lighting Division, Development Laboratory, Turnhout (Belgium).

Although this type proved satisfactory for many years, and is still widely used, it has certain practical disadvantages. The first is the increasing absorption of light by the dust and dirt accumulated on the vacuum jacket, not merely on the outside but on the inside too. The latter is due to the far from hermetic seal between lamp and vacuum jacket. Every time the lamp heats up and cools down again, air is expelled and then again drawn into the jacket, bringing dirt with it.

A second drawback is the gradual decline in the thermal insulation provided by the vacuum jacket, owing to deterioration of the vacuum. Unlike the accumulation of dirt, this trouble is not immediately perceptible, but it can seriously impair the efficiency of the lamp, whether old or new.

To avoid these difficulties, designs were introduced some years ago in which the discharge tube was hermetically sealed within the insulating

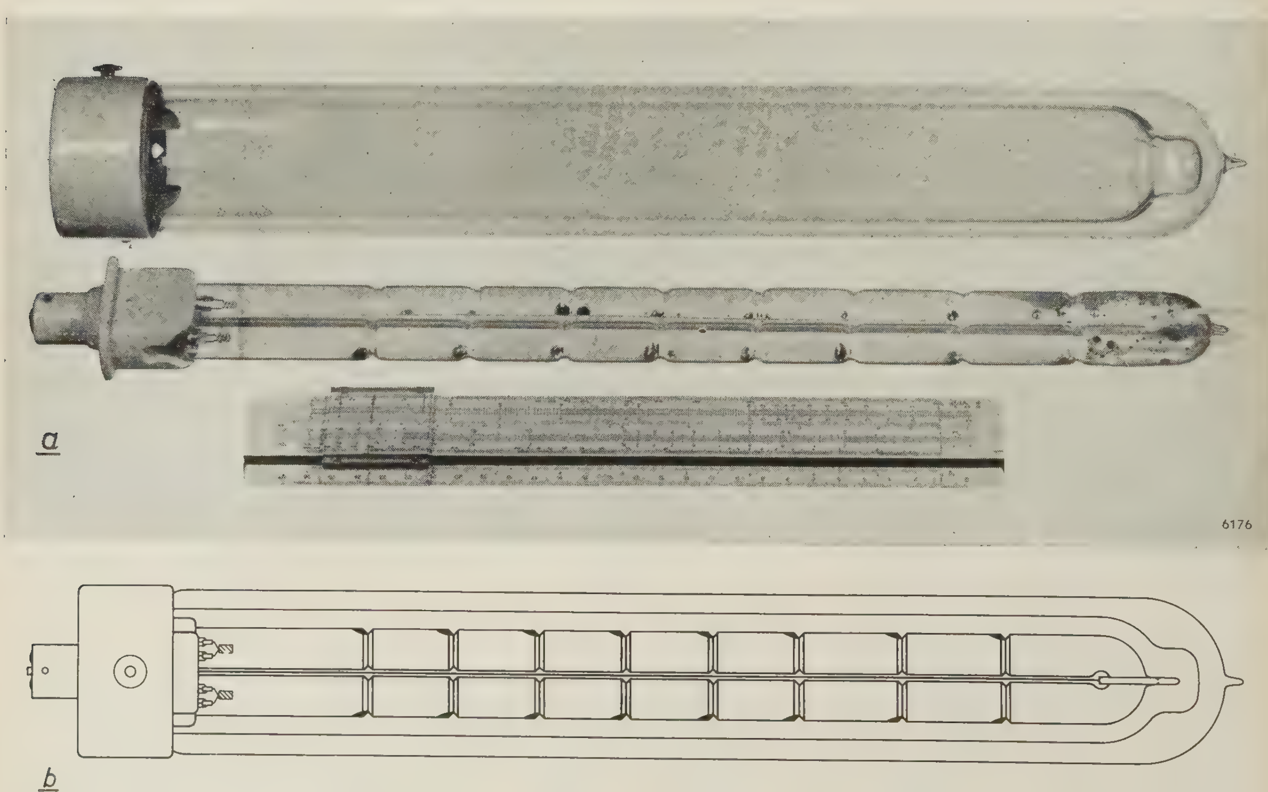


Fig. 1. *a*) Photograph and *b*) cross-section of a type SO 140 W sodium lamp. The U-shaped discharge tube is enclosed in a detachable vacuum jacket.

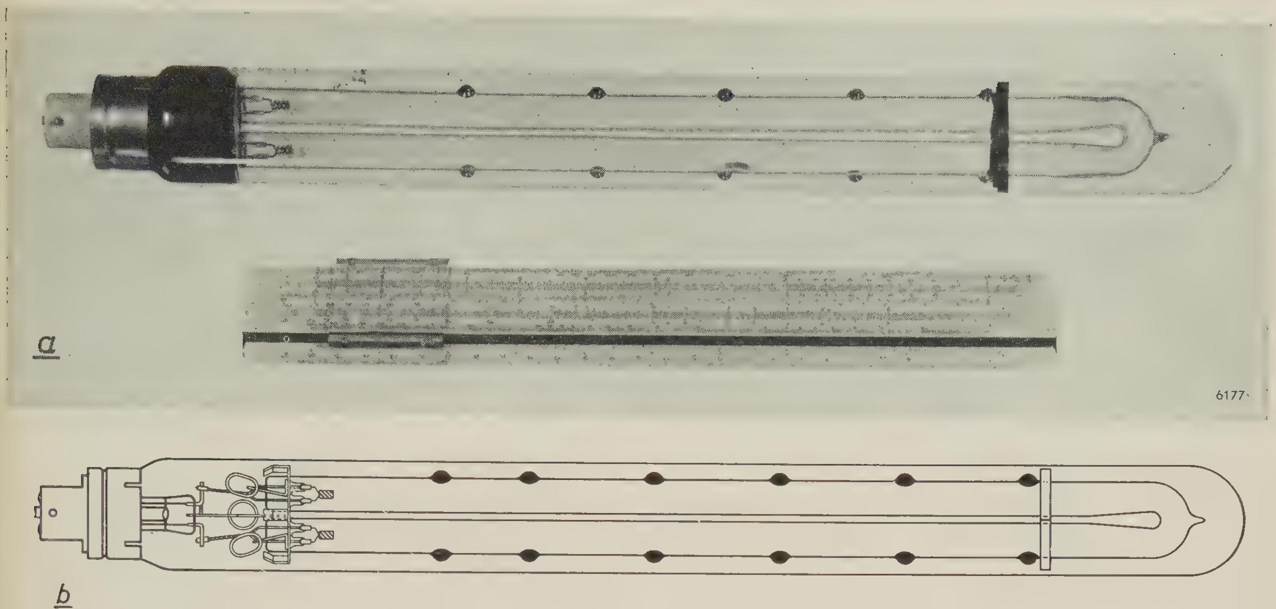


Fig. 2. *a*) Photograph and *b*) cross-section of an integral type SO 140 W sodium lamp, with single-walled non-detachable vacuum jacket. The discharge tube contains protuberances for holding the sodium in place.

jacket. This idea was by no means new, "integral" lamps of this kind having been marketed as long ago as the 'thirties [1]). It is only in recent years, however, that full benefit has been derived from the advantages of this more expensive construction, new techniques having made it possible to achieve higher efficiencies and a more constant luminous flux.

In this "integral" type of lamp, marketed by Philips in a more modern form in 1958, the separate double-walled vacuum jacket was replaced by a single-walled tubular envelope in which the discharge tube was permanently mounted. The space between discharge tube and envelope was evacuated. A modern gettering method made it possible to maintain the high vacuum throughout the life of the lamp. The discharge tube was provided with small protuberances for containing the sodium (*fig. 2a* and *b*) [2]). A range of these lamps was developed for ratings of 45, 60, 85 and 140 W. Lamps having a detachable vacuum jacket were immediately replaceable by lamps of the new type, giving a much more constant luminous flux.

In the further development of the integral sodium lamp it was found that a somewhat more complicated design offered even greater gains, both as regards efficiency and constancy of luminous flux. As a result of better thermal insulation, for example, it proved possible to achieve, and indeed exceed, the unprecedented efficiency of 100 lm/W in a sodium lamp suitable for practical use.

The improved thermal insulation was obtained by means of a separate glass "sleeve" fitted around the U-shaped discharge tube inside the evacuated bulb (*fig. 3a* and *b*). This sleeve radiates part of the heat emanating from the discharge tube back into the interior [3]).

In the lamps illustrated in fig. 2 the outer bulb also radiated energy back to the discharge tube. With the double-walled form shown in fig. 3, however, the effect is considerably greater, owing to the fact that the reflecting glass wall (of the sleeve) can get hotter than in the single-walled construction. Consequently the heat loss is smaller and the efficiency higher. This improved design is used in lamps rated for 45, 60, 85, 140 and 200 W, which were first marketed in 1960 under the type designation SOI.

Table I surveys the luminous efficiencies obtained with sodium lamps in the forms introduced in 1956, 1958 and 1960. The figures relate to 140 W lamps.

[1]) W. Uyterhoeven, Elektrische Gasentladungslampen, Springer, Berlin 1938, p. 216.

[2]) For further particulars of this type of lamp, see W. Verwey and M. H. A. van de Weijer, New sodium lamps, Communic. P-59.22 of the 14th Session of the International Commission on Illumination, Brussels 1959.

[3]) In 1955 the (British) General Electric Company brought out a sodium lamp with a narrow sleeve fitted around each limb of the U-shaped discharge tube.

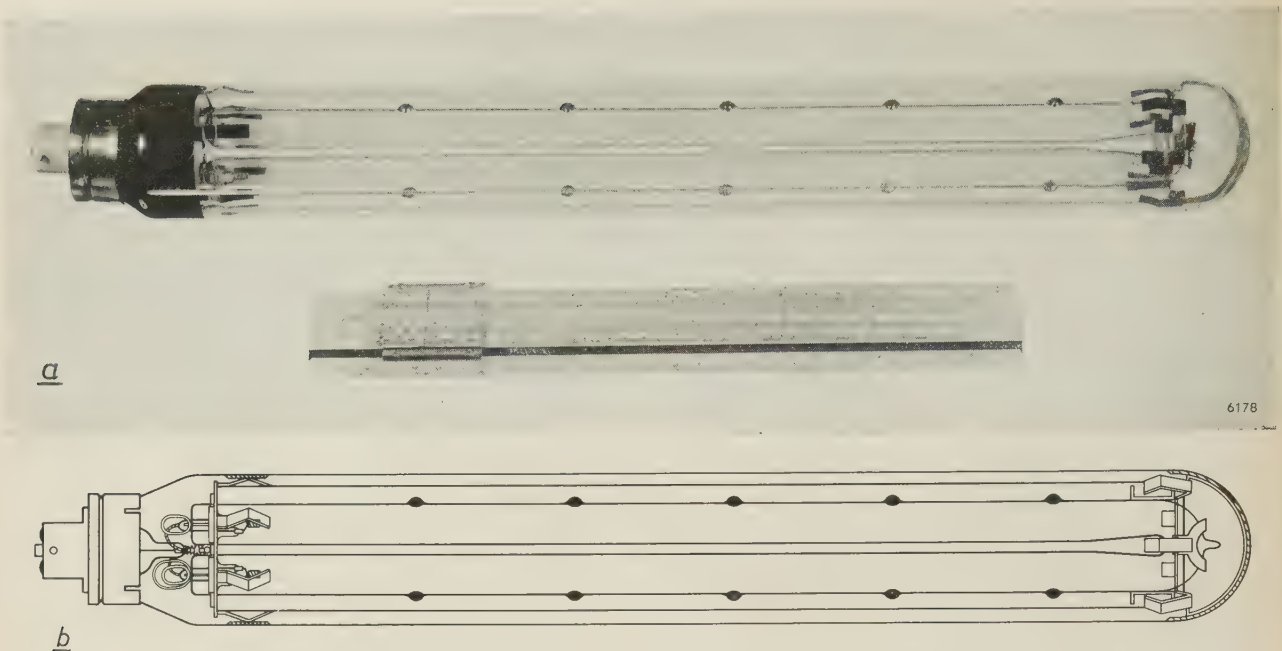


Fig. 3. *a*) Photograph and *b*) cross-section of a type SOI 140 W sodium lamp, with vacuum jacket and protuberances as in fig. 2. A sleeve for improving the thermal insulation surrounds the discharge tube.

Table I. Luminous efficiency of 140 W sodium lamps in designs of recent years.

Year	1956	1958	1960
Design	discharge tube in detachable vacuum jacket	discharge tube in single-walled vacuum jacket	discharge tube with sleeve in vacuum jacket
Luminous efficiency (lm/W)			
after 100 h	79	82	100
after 4000 h	52 *)	68	88

*) In a clean vacuum jacket.

To explain this development and give some idea of the further prospects of the sodium lamp, we must go somewhat deeper into the various factors governing the luminous flux, its decline during operation, and the life of the lamp. Principal among these factors are:

1) the thermal insulation around the discharge tube,
2) the rare gas added (for initiating and maintaining the discharge),
3) the shape and size of the discharge tube,
4) the composition of the glass of which the discharge tube is made.

Effect of thermal insulation on luminous efficiency and luminous flux

The operating principle of the sodium lamp is to excite as efficiently as possible the resonance radiation of sodium (wavelengths 589.0 and 589.6 nanometres). (1 nanometre (nm) $= 10^{-9}$ m.)

The luminous efficiency is closely dependent on the vapour pressure of the sodium. Since all sodium lamps operate with saturated sodium vapour, the vapour pressure is determined by the temperature of the discharge tube. If the vapour pressure is too low (temperature too low), the number of sodium atoms capable of being excited is too small. If the vapour pressure is too high, self-absorption predominates, i.e. the sodium atoms absorb too much of the resonance radiation themselves. There is consequently one optimum vapour pressure, and that amounts to roughly 4×10^{-3} torr (1 torr = 1 mm Hg), corresponding to a tube temperature of about 270 °C [4]).

The temperature of the discharge tube is governed on the one hand by the power consumed, and on the other by the thermal insulation. Assuming that the same tube temperature of, say, 270 °C is desirable in all forms of sodium lamp, this means that if the thermal insulation is changed the power consumption must also be changed in order to maintain the optimum temperature: improved insulation calls for less power, and vice versa. In comparing the properties of particular lamp constructions, we take each lamp at its op-

[4]) Uyterhoeven, loc. cit. p. 205. Other lamp parameters affect this optimum temperature, e.g. the pressure of the added rare gas (see p. 252 of this article). This explains why other optimum values are sometimes mentioned in the literature.

timum working point. The construction with the best thermal insulation then has the highest luminous efficiency. To obtain good thermal insulation it is necessary to take measures to counteract losses due to convection and conduction as well as the total loss due to radiation.

Convection and conduction losses depend primarily on the vacuum around the discharge tube. In *fig. 4a* and *b* it can be seen how the efficiency η and the optimum power P depend on the residual pressure p_0 in the vacuum jacket when the lamps are not exposed to wind and when they are. The graph shows clearly that the vacuum inside the jacket has to meet high requirements. It is maintained by a barium film deposited on the inside of the outer bulb. Practically all the gases gradually released during operation are removed by chemical combination with the barium. The film is of course deposited at a position where it does not obstruct the emission of light.

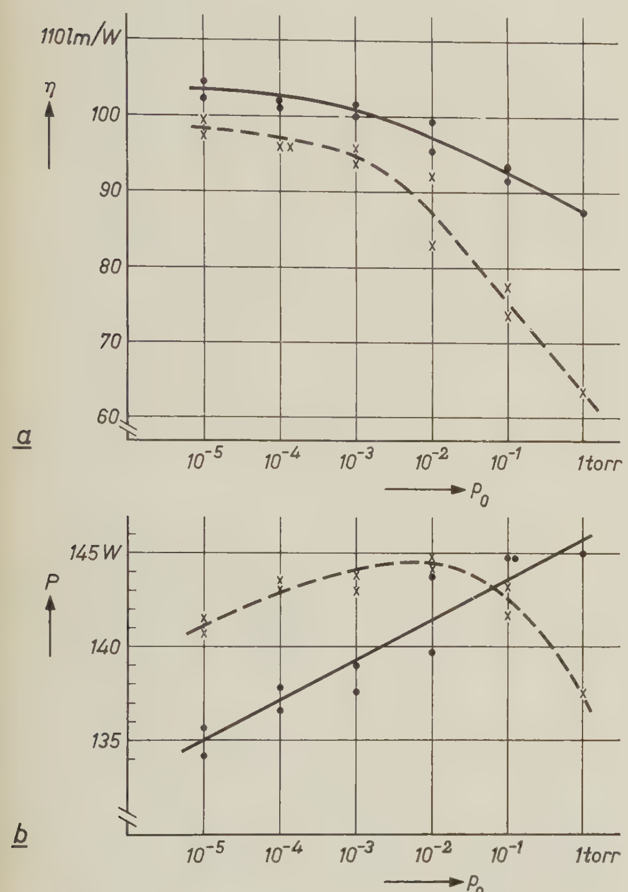


Fig. 4. *a*) Luminous efficiency η, and *b*) optimum power consumption P, of a sodium lamp (type SOI 140 W), as a function of the pressure p_0 of the gas (argon) in the outer bulb. The solid curves relate to operation out of the wind, the broken curves to exposure to wind.

The radiation losses can be limited in two ways:

a) Thermal energy radiated by the discharge tube is absorbed by a surrounding jacket. This consequently gets hot and radiates heat back to the discharge tube. The sleeves mentioned work largely along the same lines.

b) Thermal energy radiated by the discharge tube is directly reflected by the surrounding jacket. As we shall see, the discharge tube radiates mainly in the infrared, with a peak at about 5 μ. Since glass reflects only about 14% of radiation at these wavelengths, it is necessary in this case to coat the glass with some substance which is an effective reflector of infrared rays.

Both methods are discussed below.

Limitation of radiation losses by means of sleeves

The function of the sleeves, then, depends mainly on absorption and to a slight extent on the reflection of infrared radiation. The hot sleeve radiates outwards as well as inwards. The outward radiation can in turn be intercepted by a second sleeve around the first, and so on. Radiation losses can thus be progressively reduced by increasing the number of sleeves. In each case, however, the reduction becomes successively smaller, whereas the absorption of light (2.5% to 3% per sleeve) becomes more and more of a nuisance. These effects are illustrated in *Table II*.

The table clearly demonstrates that, as mentioned above, an improvement in insulation is accompanied by a smaller optimum power loading. As a result of this effect the luminous flux decreases more steeply than it would be increased by the greater efficiency if the power were constant. The

Table II. Influence of the number of sleeves, under optimum load (P_{opt}), on the luminous flux Φ_{la} and the luminous efficiency η_{la} of the lamp (including sleeves) and on the luminous flux Φ_t and efficiency η_t of the discharge tube. The figures relate to a U-shaped discharge tube having an inside diameter of 12 mm and an arc length of 666 mm.

Cross-section	number of sleeves	P_{opt}	lamp		disch. tube alone	
		W	Φ_{la} lm	η_{la} lm/W	Φ_t lm	η_t lm/W
	0	127	11300	89	11600	91.5
	1	96	9400	98	9900	103
	2	80	8150	102	8800	110
	3	70	7200	103	8000	114

sleeves thus improve the efficiency but reduce the luminous flux, and at the same time they make the lamp larger and more fragile. For these reasons no more than one sleeve is used in present-day sodium lamps.

Limitation of radiation losses by means of an infrared-reflective coating

For further improvement of the thermal insulation better results can be expected from the second method mentioned, i.e. the application of a coating around the discharge tube for effectively reflecting the infrared rays. A coating of this kind, applied to the sleeve or to the inside of the outer envelope, must of course readily transmit the sodium light.

The radiant power emitted in the infrared by the discharge tube is roughly equivalent to that from a black body having a temperature of about 545 °K (270 °C). At this temperature the spectral distribution of the radiant power from a black body is as shown in *fig. 5*. The coating to be applied must therefore be an especially good reflector at wavelengths of about 5 μ.

In about 1930 investigations were made at Philips into the usefulness of metallic layers as

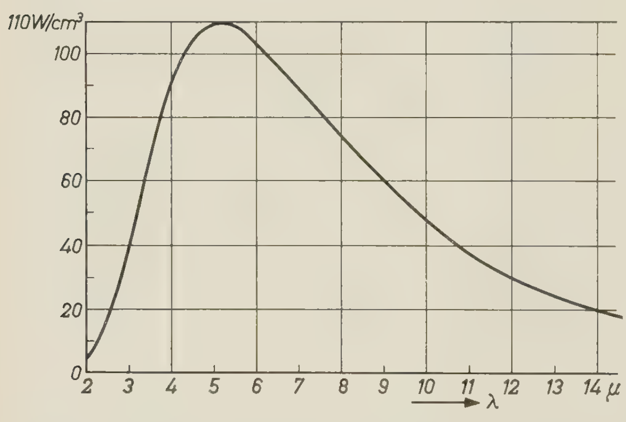


Fig. 5. Spectral distribution of the radiant power from a black body at 545 °K. The power in watts per square centimetre of radiating surface and per centimetre wavelength interval is plotted against the wavelength.

infrared reflectors for sodium lamps [5]). This work has been continued by Kauer of Philips Zentrallaboratorium GmbH, Aachen, and by Van Alphen of Philips Research Laboratories, Eindhoven. Without going into the theory, we shall mention here some of the results of the study made of metallic and metal-oxide layers.

1) *Metallic layers. Fig. 6* shows the reflection coefficient of a layer of gold at a wavelength of 5.29 μ

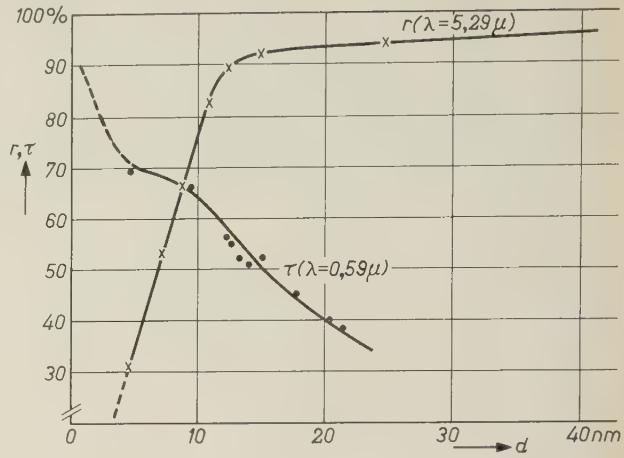


Fig. 6. The reflection coefficient r of plane gold layers at a wavelength $\lambda = 5.29$ μ, and the transmission coefficient τ at $\lambda = 0.59$ μ (sodium light), both as a function of the thickness d of the layers.

and the transmission coefficient at a wavelength of 0.59 μ (sodium light), as functions of the thickness of the layer.

To decide on the thickness of the layer it is necessary to strike the most favourable compromise between the infrared reflection and the transmission of light. For this purpose a series of sodium lamps were made, differing only in the thickness of the layer of gold on the sleeve in each lamp. The lamps thus differed in their thermal insulation and hence in their optimum power loading. *Fig. 7* shows how the optimum power, the maximum luminous efficiency and the total luminous flux vary as functions of the thickness of the gold layer.

The variation of the luminous efficiency can be explained broadly as follows. At thicknesses less than 4 nm the reflection in the infrared is practically zero, although the layer already absorbs some light. Even layers as thin as this, therefore, reduce the efficiency. Between 5 and 15 nm there is a marked increase in infrared reflection. In spite of the accompanying increase in the absorption of light, the efficiency nevertheless rises with increasing thickness up to a maximum which, in this case, had the high value of 125 lm/W at 15 nm. In layers thicker than 15 nm the reflection coefficient shows no further rise of any significance and the increasing absorption of light predominates, as a result of which the efficiency declines.

Thus, although the application of a gold layer of the proper thickness can raise the luminous efficiency from about 100 to 125 lumens per watt, the gain is accompanied by a severe decline in light output, namely from about 14 000 to some 4000 lumens. That explains why lamps of this kind have not been put on the market. Efforts are still being

[5]) Austrian patent number 134 018, granted in 1933 in the name of W. de Groot.

made, however, to improve the transmission of light by coating the gold layer with another substance to reduce its reflection of light.

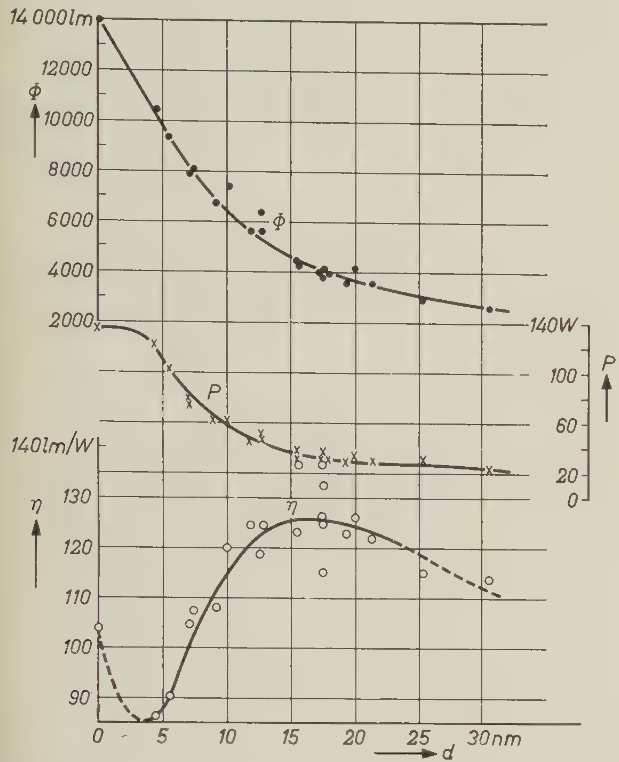


Fig. 7. Luminous flux Φ, lamp power P and efficiency η under optimum loading, as functions of the thickness d of a gold layer coated on the sleeve of a series of otherwise normal SOI 140 W sodium lamps (diameter of discharge tube 15 mm, arc length 820 mm, sleeve diameter 50 mm, outer bulb diameter 60 mm).

2) *Metal-oxide layers.* From the classical electron theory of metals it was already known that substances containing a fairly high concentration of free charge carriers would be good infrared reflectors. Substances exhibiting the required property were therefore to be expected amongst the semiconductors, provided that the concentration of free charge carriers could be made sufficiently large.

Investigations have been carried out on thin layers of metal oxides (on glass) which were known to combine transparency with a fairly high electrical conductivity [6]). The reflection coefficient is then dependent on the electrical conductivity as well as on the wavelength of the radiation. *Fig. 8* shows the reflection coefficient r of a layer of stannic oxide (SnO_2) at a wavelength of 5 μ, as a function of conductivity, together with the absorption coefficient a of the layer for sodium light.

A comparison of these curves for stannic-oxide layers with those for gold layers (fig. 6) shows that the light transmission of the stannic-oxide layers is markedly superior. It has thus proved possible with lamps of the type just described, but in which the sleeve is coated with stannic oxide instead of gold, to achieve the equally high efficiency of 125 lm/W [7]) with the considerably higher light output of about 8800 lumens (power consumption 70 W). A lamp of the same size, containing a gold layer, gives an equal efficiency with a light output of no more than 4400 lm (power consumption 35 W). It therefore looks as if the transparent semiconductor coatings offer better practical prospects than the metal layers, which are more reflective but absorb more light.

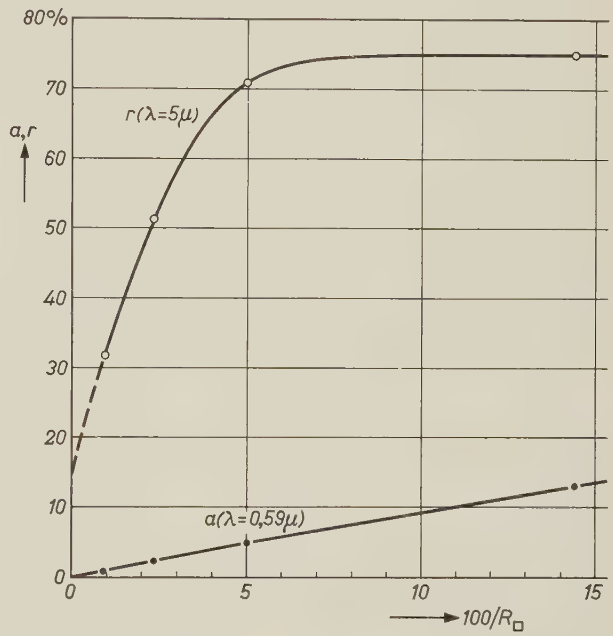


Fig. 8. Reflection coefficient r at $\lambda = 5\ \mu$ and absorption coefficient a for sodium light, as functions of the conductivity of stannic-oxide layers. The abscissa is $100/R_{\square}$, where $R_{\square}$ is the "resistance in ohms per square".

Finally it should be noted that the gain in efficiency obtained by using an infrared reflector always involves a lower lumen output, even if the infrared reflector were to transmit light for 100 %. This appears from *fig. 9a*, in which the measured luminous flux is corrected for the light absorption in the reflector (in this case a layer of gold). For this purpose separate measurements had previously been made of the light transmission of sleeves coated with gold layers of different thicknesses (fig. 9*b*).

[6]) This property makes such layers useful for other purposes, e.g. in electroluminescent panels; see Philips tech. Rev. **19**, 1-11, 1957/58.

[7]) In larger lamps, rated for 200 W, efficiencies as high as 140 lm/W have been reached.

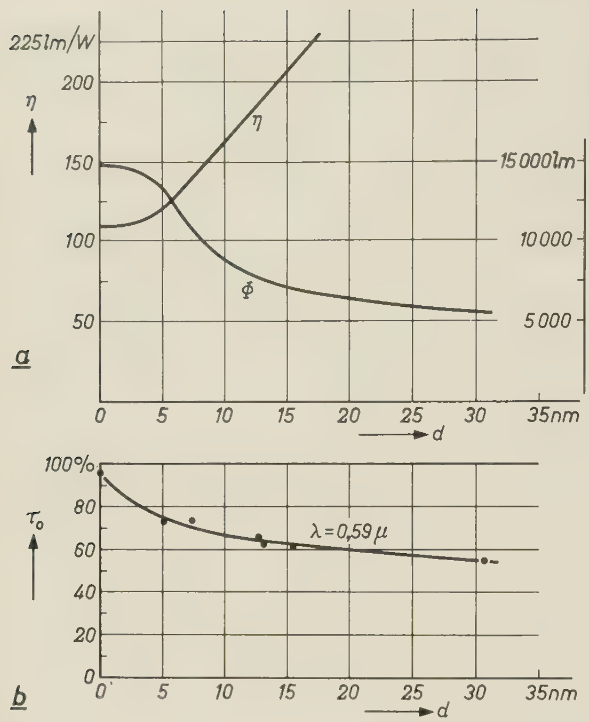


Fig. 9. *a*) Luminous flux Φ and efficiency η of a sodium lamp with a layer of gold coated on the sleeve, after correction for the absorption of light in the gold layer. The curves are derived from fig. 7 and fig. 9*b*.
b) Sodium-light transmission coefficient τ_0 of sleeve coated with gold layer, as a function of layer thickness *d*. The curve differs from that in fig. 6, which relates to a plane layer (single reflection), whereas the above curve relates to a sleeve, in which the light undergoes multiple reflections.

Influence of rare-gas pressure on luminous efficiency

The rare gas, which serves to initiate and maintain the discharge in sodium lamps, is given a pressure of about 10 torr. Under optimum power loading (temperature about 270 °C) the vapour pressure of the sodium is of the order of only 10^{-3} torr. In that case, then, there are roughly 10^4 times as many rare-gas atoms as sodium atoms present in the gas mixture. It is therefore evident that the kind of rare gas used and its pressure will have a considerable influence on the properties of the lamp. We shall confine ourselves here to mentioning some established relations between rare-gas pressure and certain properties of the lamp, such as luminous efficiency and power consumption.

The rare gas nowadays used in sodium lamps is neon, with a small admixture of argon and/or xenon to lower the ignition voltage. The effect of the pressure of a mixture of neon and argon on luminous efficiency has been investigated quantitatively by measurements on a type SOI 140 W lamp in the pressure range from 1 to 15 torr. The measurements showed that as the rare-gas pressure is decreased the maximum efficiency of the lamp increases fairly steeply: lamps with 15 torr reached 94 lm/W, lamps with 1 torr 114 lm/W. A striking circumstance is that the lamp, when operated at maximum efficiency, consumes less power at low rare-gas pressures than at high. This means that the optimum temperature of the discharge tube must also differ in these two cases, being lower at low powers than at high [8]).

We see, then, that if the rare-gas pressure is reduced, the sodium-vapour pressure — which is of course governed by the temperature of the discharge tube — must also be reduced in order to obtain maximum efficiency.

Fig. 10 illustrates how the luminous efficiency, the power consumed, the arc voltage and the lamp current vary with the rare-gas pressure under optimum loading conditions. The luminous flux Φ is also represented, and it can be seen that Φ in this case rises with increasing luminous efficiency, in

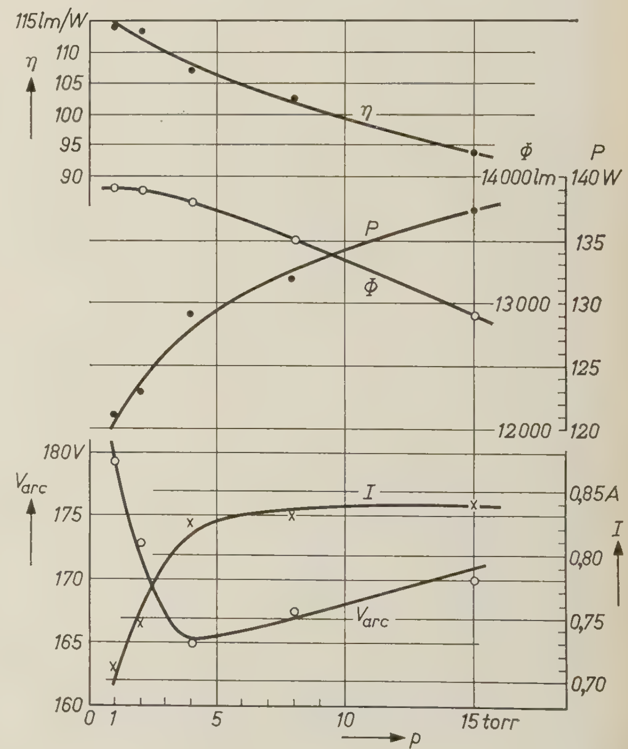


Fig. 10. Luminous flux Φ, lamp power P, efficiency η, arc voltage V_{arc} and lamp current I of an optimally loaded sodium lamp, type SOI 140 W, in dependence on the rare-gas pressure p (neon plus 1% argon).

8) We have not yet confirmed this by direct measurements, but the conclusion is reasonable, especially considering that the lowest power loading gives the highest efficiency, so that a smaller fraction of this low power is converted into heat.

spite of the lower power needed for optimum loading [9]).

The improvement in luminous efficiency which, as shown by these experiments, can be achieved by lowering the rare-gas pressure is unfortunately possible only within strict limits. It will presently be made clear why the pressure of the filling cannot be arbitrarily low.

Effect of arc length on luminous efficiency

If only the length of a sodium discharge is varied and the current is kept constant, the efficiency increases as the arc is made longer. This familiar effect is due to the fact that the electrode losses are relatively less significant in a long arc than in a short one. *Table III* shows how various properties of the lamp vary as functions of arc length. As we

Table III. Arc voltage V_{arc}, power consumption P and luminous efficiency η of a sodium discharge tube as functions of arc length. Diameter of the tube 12 mm, current 0.6 A.

Arc length mm	V_{arc} V	P W	η lm/W
280	82	45.5	80.7
405	109	61.2	89.7
615	156	85.6	98.0

[9]) First the optimum power loading was determined at every pressure by plotting efficiency versus lamp current (*fig. 11*)

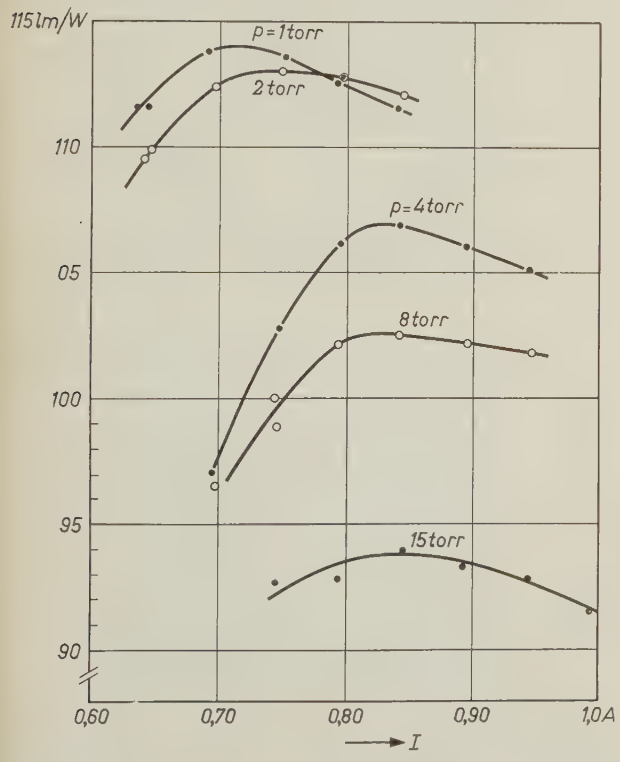


Fig. 11. Efficiency of SOI 140 W sodium lamps as a function of lamp current I, with the pressure p of the rare-gas filling (Ne + 1% A) as parameter. The maxima of the curves correspond to optimum loading conditions.

shall presently see, it is particularly important to take this effect into account when there is any reason to make the lamp shorter.

Sodium migration

Decline in light output as a consequence of sodium migration

Owing to the relatively high pressure of the rare gas in the lamp, each droplet of sodium only supplies sufficient vapour pressure for its own immediate surroundings. For this reason it has always been customary to distribute a fairly large surplus of sodium uniformly in drops over the whole surface of the discharge tube. Usually, however, the even distribution is not maintained. This is due to various causes, the main one being the differences in temperature along the wall of the tube, as a result of which the sodium tends to distil from hot to cold spots. A consequence of this migration is that the average vapour pressure of the sodium diminishes during the life of the lamp from its original, optimum value. Ultimately, all the sodium accumulates at the coldest spot in the lamp, and the vapour pressure drops to a minimum. A state may be reached where large parts of the discharge tube have hardly any sodium vapour, all the liquid sodium having accumulated at one point. The emission of sodium light from these parts is then virtually zero [10]).

Limitation of sodium migration by protuberances in the discharge tube

Sodium migration can be substantially reduced by applying the sodium droplets, during the manufacture of the lamp, to defined points along the tube that remain relatively cold. The points in question may be small protuberances in the tube wall, sufficient to hold a sodium droplet. This principle has been adopted by Philips in their more recent types of sodium lamps (figs 2 and 3).

A different method has been used in the "Linear Sodium Lamp", recently brought on to the market by the A.E.I. Lamp and Lighting Co. The tube wall in this lamp contains a number of depressions, at which positions the cross-section of the tube is not circular and has relatively cold spots where the sodium, once applied, is held in place [11]).

Suppression of sodium migration by the appropriate choice of rare-gas pressure

If for some reason or other there is a deficiency of sodium vapour in a part of the discharge tube,

[10]) Uyterhoeven, loc. cit. p. 251.

[11]) R. F. Weston, High-output sodium lamps, Electrical Times **135**, 719-722, 1959.

the discharge at that part is sustained almost entirely by the rare gas. At that part the voltage gradient is usually greater than in areas where the sodium participates properly in the discharge. Owing to the steeper gradient the part deficient in sodium consumes more power per unit length. Because of this the region where the sodium is lacking gets hotter than those well supplied with sodium, and this tends to encourage further migration. The migration thus has a cumulative character and the temperature equilibrium that initially existed becomes unstable.

It is possible, however, to choose the rare-gas filling in such a way that the power dissipated per unit length is lower in the parts deficient in sodium than in the parts well supplied. Contrary to the case just mentioned, the deficient parts then heat up less than the other parts, and sodium migrates back to where a shortage existed. The temperature equilibrium in such a tube is stable. The two cases are represented schematically in *fig. 12a* and *b*.

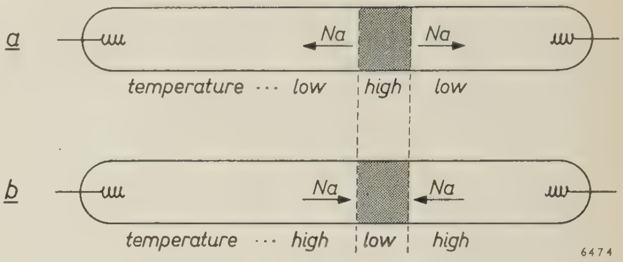
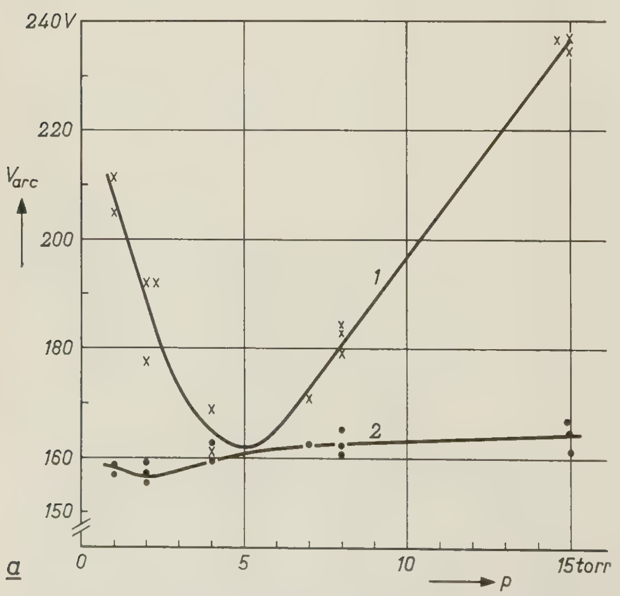


Fig. 12. Diagrammatic representation of sodium migration, (*a*) cumulative, (*b*) reduced. The shading in both cases denotes a zone deficient in sodium.
a) Classical case of relatively high rare-gas pressure. The low-sodium zone is hotter than the adjacent zones, which tends to promote migration.
b) When the rare-gas pressure is kept within specific limits, the low-sodium zone remains colder than the adjacent zones, which reduces or even eliminates migration.

This effect, in dependence on the rare-gas pressure, has been studied quantitatively on lamps containing neon plus 1% argon. The state where no sodium vapour takes part in the discharge was investigated by measuring, at room temperature and without giving the lamp a chance to get hot, the voltage gradient of the column and the power dissipated per centimetre length of column. The data thus obtained relate to the low-sodium discharge (rare-gas characteristic) [12]. The lamp was then allowed to heat up, and measurements were made of the discharge characteristic in the mixture of rare gas and sodium vapour. The arc voltage and the power consumption were determined in dependence on the rare-gas pressure for both the cold and the hot lamp.

The results of measurements on type SOI 140 W lamps are presented in *fig. 13a* and *b*. It can be seen from fig. 13*a* that at all rare-gas pressures the r.m.s. value of the arc voltage is higher in the pure rare gas than when sodium vapour is also present. Fig. 13*b* shows that there is a range of pressures in which, notwithstanding the higher arc voltage, the power consumed is lower than in the mixture of rare gas and sodium vapour. This is due to the fact that the wave-forms of the voltage in the two discharges are different (see the oscillograms in *fig. 14a* and *b*), so that the form factor — and hence the power factor a — is greater when the discharge

[12]) A discharge tube containing no sodium was investigated to ascertain whether the rare-gas characteristics differed at 20 °C and 270 °C. This proved not to be the case.



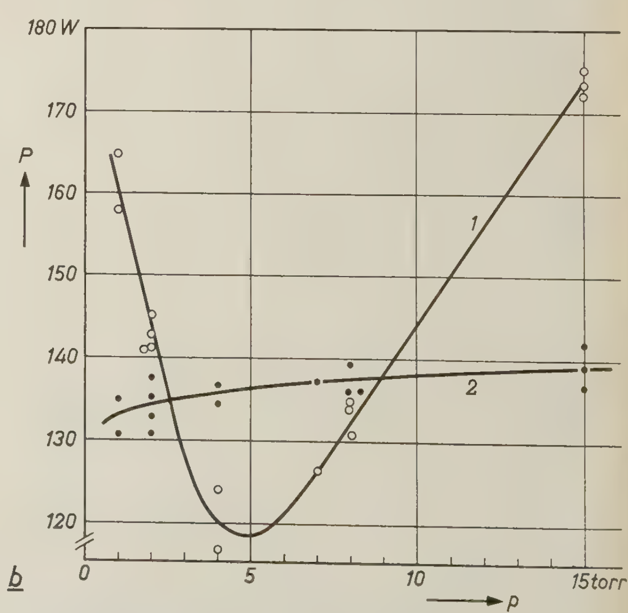


Fig. 13. *a*) Arc voltage V_{arc} (r.m.s. value) and *b*) lamp power P as a function of the pressure p of the rare-gas filling (Ne + 1% A); curves *1* without and curves *2* with sodium vapour. Measured on a standard SOI 140 W sodium lamp.

takes place in a mixture of rare gas and sodium vapour than when no sodium vapour is present. The values measured on the above-mentioned lamps were $a = 0.83$ for the discharge in rare gas alone, and $a = 0.94$ for the discharge in rare gas with sodium vapour.

In the region from 3 to 8 torr it is reasonable, in view of the temperature differences caused, to expect self-stabilization of the sodium distribution. In this way, then, the decline in light output due to sodium migration is effectively reduced.

For simplicity we have disregarded here the effect of the rare-gas pressure on the optimum working point of the lamp. In fact, as indicated, the lamp currents for maximum efficiency must be smaller at lower rare-gas pressures. This has no influence, however, on the effect described, the pressure region concerned remaining virtually unchanged.

A life test on type SOI 140 W lamps, with rare-gas pressures of 6 and 9 torr, confirmed the stabilizing effect of the lower pressure. The measured efficiencies are collected in *Table IV*. After 5000 hours, marked migration was observed in the lamps with 9 torr, whereas in the lamps with 6 torr hardly any sodium was found outside the original points.

a

b

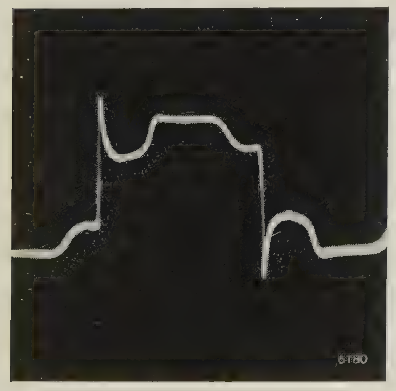


Fig. 14. Oscillograms of the arc voltage of a discharge in rare gas (Ne + 1% A, pressure 8 torr), *a*) without, *b*) with sodium vapour. Measured on a standard sodium lamp type SOI 140 W, lamp current 0.9 A. The difference in wave-form explains the smaller form factor in *a*) than in *b*).

Table IV. Efficiency of type SOI 140 W sodium lamps, during a life test with rare-gas pressures of 9 and 6 torr (Ne + 0.5% A).

Rare-gas pressure	efficiency in lm/W, measured after					
	100 h	1000 h	2000 h	3000 h	4000 h	5000 h
9 torr	97.7	94.6	91.9	88.2	81.7	81.4
6 torr	102.7	97.9	96.0	94.6	95.8	93.9

Decline in light output owing to glass discolouration

Sodium is chemically an extremely aggressive substance, particularly in vapour form, and quickly attacks all ordinary kinds of glass. The surface layer of the glass exposed to sodium vapour takes up a large quantity of sodium, and as a result turns brown. In certain cases concentrations of 2.1×10^{22} sodium atoms per cm^3 have been found in the brown layer; this implies that the average distance between the sodium atoms in the layer is less than twice that in metallic sodium [13]).

The discolouration of the glass obviously entails considerable absorption of light. Moreover, due to the uptake of sodium the composition of the glass changes and so too therefore does the coefficient of expansion; the consequent stresses may become so high as to crack the glass, prematurely ending the life of the lamp.

To avoid these effects, special kinds of glass have been developed to withstand the influence of sodium vapour under the conditions prevailing in a sodium lamp, without any significant discolouration. However, a serious drawback of these non-discolouring types of glass is the marked extent to which, in general, they adsorb argon.

Life of the gas filling

As stated, the rare-gas filling in present-day sodium lamps is neon with small admixtures of argon or xenon, or both. These admixtures, which are essential for lowering the ignition voltage [14]), steadily diminish in concentration during the life of the lamp, owing to adsorption, particularly at the glass wall. The gas filling will finally consist of almost entirely pure neon, resulting in such a high ignition voltage that the lamp can no longer be started by the available open-circuit voltage. The lamp is then said to have reached the end of its "gas life" (as opposed, for example, to the "cathode life").

[13]) J. W. Wheeldon, Absorption of sodium and argon by glass, Brit. J. appl. Phys. **10**, 295-298, 1959.

[14]) F. M. Penning, Über Ionisation durch metastabile Atome, Naturwiss. **15**, 818, 1927; Über den Einfluss sehr geringer Beimischungen auf die Zündspannung der Edelgase, Z. Phys. **46**, 335-348, 1927/28.

The rate at which the glass wall adsorbs rare gases depends primarily on the following factors:
1) the pressure of the rare gas,
2) the voltage gradient in the column,
3) the composition of the glass used for the discharge tube.

When the lamp is burning, ions are formed not only from the sodium but also from the rare gas, in particular from the argon, which has a lower ionization voltage than neon. These (positive) rare-gas ions are attracted to the negatively charged glass wall, which they strike with a certain energy. If the energy upon impact is high enough, the ions — possibly after recombination with electrons — are trapped in the wall. The energy at which the ions impinge upon the wall increases with the field strength, i.e. with the voltage gradient in the column, and also with the free path, i.e. with decreasing rare-gas pressure. Whether the wall in fact continues to hold the ions depends further on the structure of the glass.

The rare-gas pressure needed for the lamp to attain a specific life is plotted in *fig. 15* as a function of the voltage gradient in the column, for two different compositions of glass. The lamps in question were experimental types filled with neon plus 0.5% argon. The curves show that the gas life is longest when the gas pressure is relatively high and the gradient in the column small; the composition of the glass is seen to have a considerable influence.

Of course it is a simple matter to employ a high gas pressure, but, as we have seen, this leads to low efficiency and a marked decline in light output during the life of the lamp. Both reasons are in fact a strong argument for a low pressure.

A low voltage gradient in the column can be obtained by using a wide discharge tube. If the sodium lamp is to have the correct operating temperature the choice of a wider tube must be associated with a higher current, i.e. with a lower lamp voltage at a specified power loading; in other words the lamp must be made shorter. A lower lamp voltage, however, entails relatively higher electrode losses and hence a lower efficiency (see Table III). The scope for lowering the voltage gradient is thus restricted.

The crux of the problem of achieving a satisfactory gas life is therefore the composition of the glass.

As remarked above, those types of glass that are not turned brown by sodium vapour generally have the disadvantage of strongly adsorbing rare gases. Recently, however, types of glass have been developed that show relatively favourable properties in both respects [15]). With glass of this kind it has

[15]) Due in particular to the work of C. M. La Grouw, Glass Development Centre, Eindhoven.

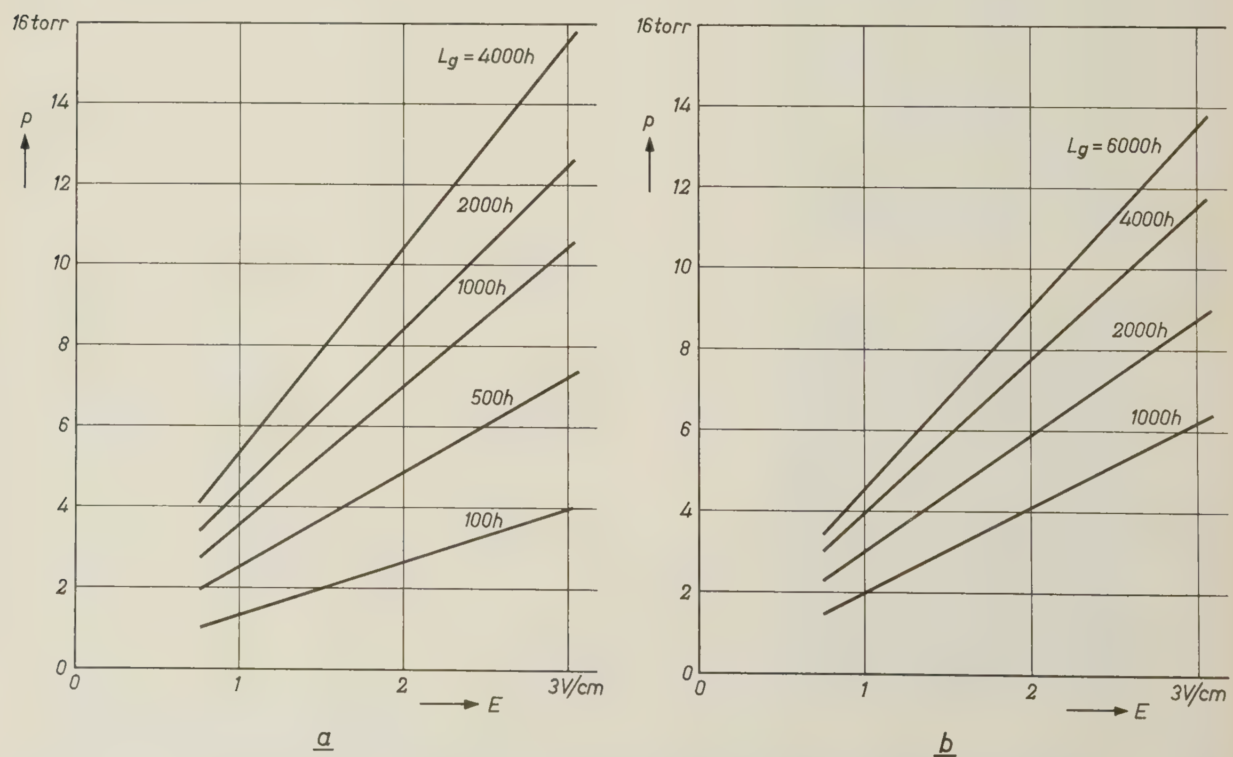


Fig. 15. The lowest rare-gas pressure p (Ne + 0.5% A) needed for a sodium lamp to attain a specific "gas life" L_g, as a function of the voltage gradient E in the column. The lines b relate to a better type of glass (adsorbing less argon) than lines a.

proved possible to reduce the pressure of the neon-argon mixture to 8 torr for a gradient of 1.8 V/cm in the column, ensuring a gas life of at least 6000 hours.

Future prospects

We shall now briefly examine the further evolution of sodium lamps that may be expected in the not too distant future.

Thermal insulation

From what has been said in the foregoing, it will be evident that there is still ample scope for refinements in the use of infrared-reflecting layers. It is by no means unlikely that advances in this direction will make it possible to produce sodium lamps giving an efficiency of 150 lm/W or even more. These lamps will be bulky, however, since if the thermal insulation is improved the optimum temperature of the lamp can only be maintained by reducing the power loading of the discharge tube per unit surface area.

Another potential development, running parallel with this, is therefore the construction of sodium lamps that combine a high lumen output with a relatively small size. The thermal insulation of such lamps would have to be deliberately poor in order to make a high power rating possible. For instance, a type SOI 140 W discharge tube, without an insulating jacket, has been found to give a luminous flux of more than 19 000 lm at 300 W, representing an efficiency of scarcely 60 lm/W. By means of a jacket offering very good thermal insulation and light transmission, the efficiency of the same discharge tube might be raised to perhaps 200 lm/W; the power consumed would then be only 35 W and the light output 7000 lumens. These widely divergent possibilities are probably both of importance, since lamps with the emphasis on efficiency can be developed at the same time as others with the emphasis on light output.

Rare-gas pressure

The use of lower filling pressures than have hitherto been feasible may lead to a further increase in efficiency, together with a luminous flux that will remain practically constant throughout the life of the lamp. These advantages might be achieved with a neon-argon pressure of 5 or even 4 torr. Such low pressures are not yet feasible because of the too rapid adsorption of argon by the glass in its present composition. It may be assumed, however, that the last word has not yet been said on the development of types of glass that are not turned brown by sodium vapour whilst at the same time adsorbing little rare gas.

If the filling pressure could be reduced to about 2 or 3 torr, the quantity of sodium used per lamp could also be considerably reduced, so that only a very small surplus of liquid sodium would be needed at the working temperature (just as the surplus of fluid mercury is very small in tubular fluorescent lamps). The present protuberances in the discharge tube (figs 2 and 3) could then be dispensed with, without the risk of any troublesome migration.

If, instead of a mixture of rare gases, one pure rare gas were to be used, it would already be possible to operate with a very low filling pressure, with all its attendant benefits. True, the lamps would then have a very high ignition voltage, but with a suitable ballast this need be no insuperable obstacle. The length to which one could go in this direction is limited by the life of the cathode, which is shortened when the filling pressure is reduced.

Use of other rare gases

After a thorough study has been made of the properties of gas discharges in mixtures of rare gases and sodium vapour, it may well be concluded that other rare gases offer more advantages as a filling than the classical neon. In cases of poor thermal insulation, for example, helium has proved to result in a higher efficiency than neon.

Renewed fundamental research into the sodium discharge should narrow the gap that still exists between the efficiency achieved in practice and the maximum efficiency theoretically possible, which is in the region of 450 lm/W. Notwithstanding the results achieved, the width of that gap makes it plain that we still have a long way to go.

Summary. Recent improvements in the sodium lamp concern in particular the luminous efficiency. With a lamp suitable for practical use the unprecedented efficiency of 100 lm/W has now been reached and even surpassed.

The author discusses the background of these advances and of others expected in the future, with particular reference to the influence of thermal insulation, rare-gas pressure and glass composition.

The use of infrared-reflecting layers on the glass — especially of transparent semiconductors, such as stannic oxide — is likely to result in considerably higher efficiencies, possibly up to 150 lm/W, though at the expense of making the lamps bulkier.

A promising trend is the development of types of glass that are not turned brown by sodium vapour and also adsorb little argon. Further progress in this field should lead to rare-gas pressures low enough for the light output of sodium lamps to remain almost constant throughout their life. The present protuberances in the discharge tube, which serve to hold the liquid sodium, can then be dispensed with.

Apart from the development of lamps of extremely high efficiency, lamps of lower efficiency but with smaller dimensions and a high light output are also to be expected.

LIGHTING OF TRAFFIC ROUTES

by J. B. de BOER *).

628.971.6

This article sets out to provide a survey of present-day views on the lighting of roads for motorized traffic. The first part deals with various conditions with which a road lighting installation should comply and discusses the more important experiments and considerations that have led to the drawing up of codes of practice or recommendations for meeting these conditions.

The light sources mainly used nowadays for traffic routes are incandescent (tungsten-filament) lamps, sodium lamps, high-pressure mercury-vapour lamps and fluorescent lamps. In the second part of this article these kinds of light source are compared at various points. The first point relates to the kind of light used, i.e. the spectral composition, and we shall see what bearing this has on the recommendations discussed. The second point concerns the significance of the dimensions, shape and luminance of the light sources, and the third their sensitivity to variations in temperature and voltage.

Recommendations on the lighting of traffic routes

The primary object of road lighting is to provide motorized traffic with suitable conditions for vision when daylight is no longer adequate. The lighting should preferably enable vehicles to proceed safely without the use of headlights. Experience and special experiments have shown that for this purpose there are three conditions to be fulfilled: the average road-surface luminance must be sufficiently high, the lanterns of the installation must not cause troublesome glare, and the road-surface luminance must be sufficiently uniform. We shall deal with these three conditions in turn. In doing so we shall distinguish between two aspects, namely "visual comfort" and "perceptibility". It has become increasingly clear that reasonably satisfactory perceptibility is no guarantee that the driver can also see comfortably. Visual comfort is not something that can be measured exactly. All one can do is to ask numerous observers for their appraisal of a given lighting situation, or allow each observer to alter the lighting situation to suit his own visual comfort. As may be expected, the appraisals of the same situation by different observers — or of a given situation by one observer at different times — differ considerably. Useful results can only be obtained by careful statistical analysis of a mass of data.

*) Philips Lighting Division, Lighting Laboratory, Eindhoven.

Average road-surface luminance

As regards the average road-surface luminance, we consider a value of about 2 cd/m² (0.6 footlambert) as a reasonable compromise between what is desirable and what is technically and economically feasible. Depending on the expected depreciation in light output due to dust and dirt, the design should then be based on 3 to 4 cd/m². Installations designed before 1955 seldom exceed 0.5 cd/m² under operating conditions, i.e. after a certain degree of dirt accumulation. From the results of a number of experiments we shall show that 2 cd/m² for traffic routes is certainly not too much to ask.

To obtain some idea of the road-surface luminance at which motorists feel the need to use their own lighting, i.e. to switch over from side lights to dipped headlights, observations were made at dusk of vehicle lighting as a function of the average luminance of the road surface. The results are presented in *fig. 1*. Curves *O*, *P*, *C* and *R* relate to observations on unlighted roads with little traffic, the latter to exclude as far as possible the interfering effects of oncoming traffic. Curve *C* (percentage with dipped headlights) shows that at 2 cd/m² only 10% thought the assistance of their own lights necessary.

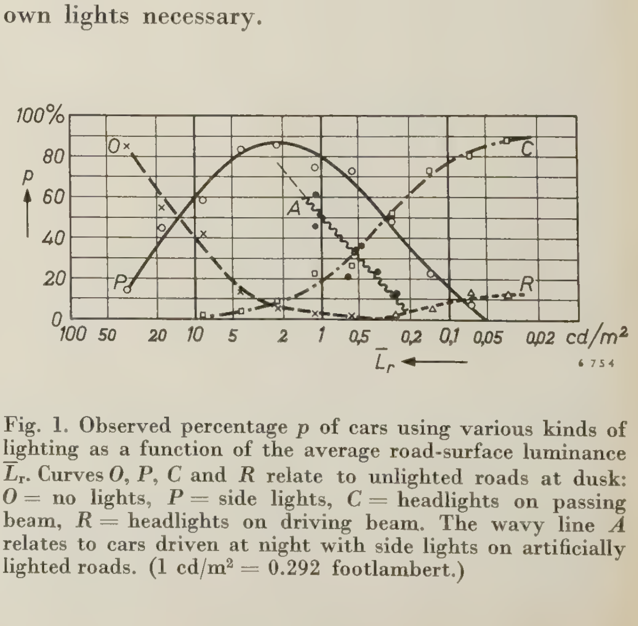


Fig. 1. Observed percentage p of cars using various kinds of lighting as a function of the average road-surface luminance $\bar{L}_r$. Curves *O*, *P*, *C* and *R* relate to unlighted roads at dusk: *O* = no lights, *P* = side lights, *C* = headlights on passing beam, *R* = headlights on driving beam. The wavy line *A* relates to cars driven at night with side lights on artificially lighted roads. (1 cd/m² = 0.292 footlambert.)

The problem was approached from the other side by making recordings of drivers travelling at night with side lights on artificially lighted roads. Extrapolation of the wavy line *A*, which represents the results of these recordings, shows that at 2 cd/m² about 75% of the drivers felt they were able to do without their headlights.

Further data on the desired average luminance of the road surface was obtained by asking a group of 16 observers (mostly engineers responsible for public lighting in Dutch towns) for their appraisal of the "lighting level" provided by the lighting installations in 70 streets [1]). The observers were also asked to assess the general impression, the non-uniformity of the luminance of the road surface and the glare caused. An appraisal of the lighting level amounts to assessing the road-surface luminance, while trying not to be unduly biased by unevenness in this luminance or by glare. The observers could express their assessment in the ratings bad, inadequate, fair, good or excellent, or with some intermediate qualification. At the same time the average road-surface luminance was measured. *Fig. 2* shows the result of the assessments of the lighting level. Each point represents the average of 16 assessments of one street. (For the purpose of averaging, the odd numbers from 1 to 9 were assigned to the successive ratings.) Through the 70 points thus obtained a curve was drawn by a common statistical method. The value of the average road-surface luminance corresponding, according to this curve, to the rating "good" (number 7) amounts to 1.5 cd/m². Statistical analysis has demonstrated that this value lies between 1.3 cd/m² and 1.8 cd/m² with a reliability of 95%. It may be noted in this connection that observers very probably rate the lighting level in a street higher the less important the street is for traffic. Of the 70 streets in question 28 were of little importance to vehicular traffic, so that the figure of 1.5 cd/m² is probably on the low side. At all events, these experiments too show that 2 cd/m² is a reasonable value to aim at.

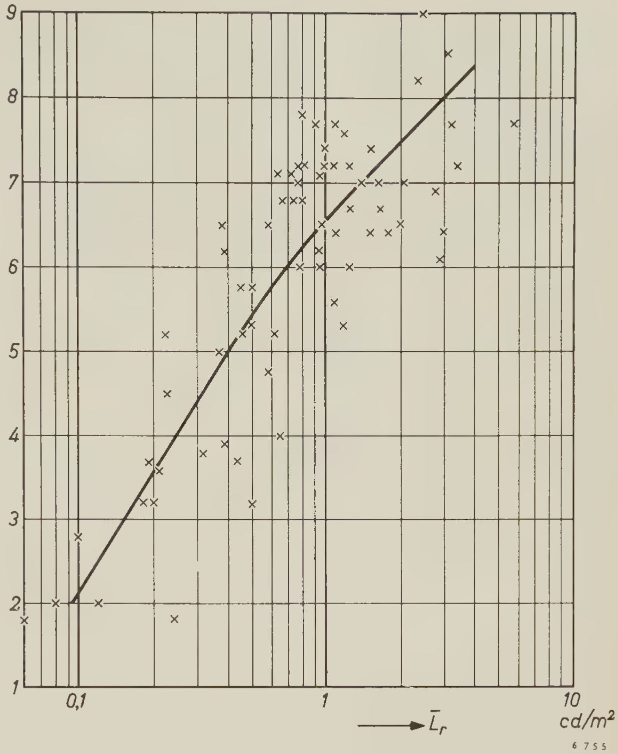


Fig. 2. Average assessment of the "lighting level" in 70 streets by a group of 16 experts. The average road-surface luminance $\bar{L}_r$ is plotted versus the following ratings: 1 = bad, 3 = inadequate, 5 = fair, 7 = good, 9 = excellent.

We have so far been concerned with visual comfort, and we now turn to the question of perceptibility. Numerous experiments have been carried out to investigate perceptibility as a function of average road-surface luminance. We have untertaken investigations of this kind on an experimental road equipped with a special lighting installation [2]). A number of observers were stationed at a fixed point along this road. At distances between 50 and 200 m from these observers, objects measuring 28×28 cm were made to appear and disappear on the road at places and times that were not known to the observers. These objects (*fig. 3*) were observed against the background of the road surface. The average luminance $\bar{L}_r$ of the surface and the ratio L_r/L_0 (L_r being the luminance of the section of road

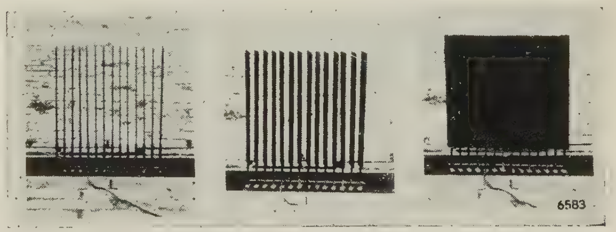


Fig. 3. Objects measuring 28×28 cm used in road perceptibility tests. The (average) luminance of the object was adjusted by means of the position of the vanes, varied by remote control. The object was not visible to the observer when all vanes were in line with him.

[1]) J. B. de Boer, F. Burghout and J. F. T. van Heemskerck Veeckens, Appraisal of the quality of public lighting based on road surface luminance and glare, Proc. Int. Comm. on Illumination, Brussels 1959.

[2]) J. B. de Boer, Fundamental experiments on visibility and admissible glare in road lighting, Proc. Int. Comm. on Illumination, Stockholm 1951.

surface against which the object is seen, and L_0 the luminance of the object) could be independently varied. We determined the minimum value that L_r/L_0 must have in order to make the object visible. For objects of the size mentioned the distance from the observer was found to be of little influence. Curve *1* in *fig. 4* gives the average for numerous observations and observers. It can be seen that, for a road-surface luminance of 2 cd/m^2, the ratio L_r/L_0 must be at least 1.7 to make our objects visible. The value of 1.7 is fairly high: a good standard for safety is that an object measuring 20×20 cm should be clearly visible at a distance of 100 m when $L_r/L_0 = 1.5$ [3]). According to our results, in spite of using larger objects this standard is far

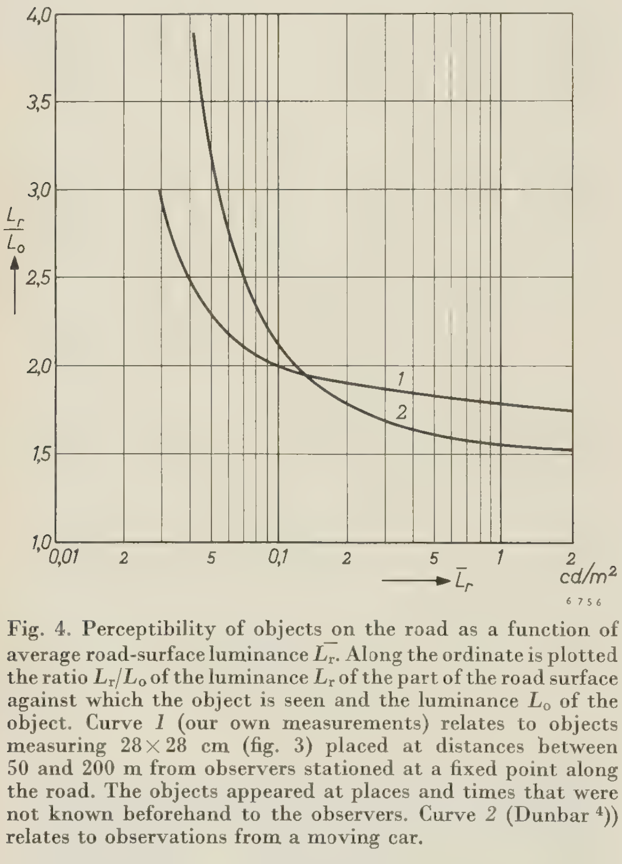


Fig. 4. Perceptibility of objects on the road as a function of average road-surface luminance $\bar{L}_r$. Along the ordinate is plotted the ratio L_r/L_0 of the luminance L_r of the part of the road surface against which the object is seen and the luminance L_0 of the object. Curve *1* (our own measurements) relates to objects measuring 28×28 cm (fig. 3) placed at distances between 50 and 200 m from observers stationed at a fixed point along the road. The objects appeared at places and times that were not known beforehand to the observers. Curve *2* (Dunbar [4])) relates to observations from a moving car.

from being satisfied at a road-surface luminance of 2 cd/m^2, and therefore as far as perceptibility is concerned the requirement of 2 cd/m^2 is in fact a modest one.

For comparison we have included in fig. 4 a curve showing the results published by Dunbar as long ago as 1938 [4]). In this investigation observations were made from a car in motion of objects one and a half times larger than ours. His results also show however, that an object with a contrast of 1.5 is still not perceptible at a road surface luminance of 2 cd/m^2.

From experiments carried out by us in 1959, also with observations from a moving car [5]), it was concluded that objects of 20×20 cm are visible from a distance of 100 m at $L_r/L_0 = 1.5$ — even to observers unprepared for the object suddenly appearing in their visual field — provided the road-surface luminance is at least 2.2 cd/m^2.

Summarizing, it can be said that an average road-surface luminance of about 2 cd/m^2 meets reasonable requirements both as to visual comfort and perceptibility. It was of course not possible to predict that these two aspects would lead to the same recommendation, and in the two points now to be discussed, glare and uniformity of road-surface luminance, we shall see that this is by no means the case.

Glare

The light sources of a road-lighting installation can give rise to a certain amount of glare (we are not concerned here with the glare caused by oncoming traffic). Investigations in recent years have made it clear that the deterioration of perceptibility (disability glare) is not nearly as important in this respect as the deterioration of visual comfort (discomfort glare). Observations have shown that as long as the glare is not troublesome, i.e. is still acceptable from the point of view of visual comfort, there is scarcely any deterioration of perceptibility [6]). In a recommendation concerning admissible glare, visual comfort is therefore the decisive factor.

As a measure of the glare caused by a light source we can take the illumination E which the light source produces on the eye of the subject. Whether glare is experienced as a nuisance depends on other conditions, the more important of which are: the average road-surface luminance $\bar{L}_r$, the angle ϑ which the line from the observer's eye to the light source makes with the horizontal, and the solid angle ω subtended by the source at the observer's eye (see sketch in *fig. 5*). The particular importance of the angle ϑ is due to the fact that, when driving in traffic, a motorist usually keeps his line of sight almost horizontal, whilst he scans the road continuously from one side to the other. The maximum

[3]) The experiments discussed were carried out before this standard was proposed, hence the differing dimensions of the objects.

[4]) E. Dunbar, Necessary values of brightness contrasts in artificially lighted streets, Trans. Illum. Engng Soc. (London) **3**, 187-195, 1938.

[5]) See the article cited under [1]), particularly pp. 9 and 10.

[6]) J. B. de Boer, Blendung beim nächtlichen Strassenverkehr, Zentralblatt Verkehrs-Medizin, Verkehrs-Psych. angr. Geb. **3**, 185-203, 1957.

value E_b which the illumination E on the eye from a single light source should not exceed if visual comfort is to remain satisfactory is thus a function of $\bar{L}_r$, ϑ and ω. In fig. 5, which gives the average result of very numerous observations by a large number of observers, E_b is plotted as a function of $\bar{L}_r$ and ϑ for three values of ω. It can be seen that if E is greater than E_b there are three possible correctives: one can either increase $\bar{L}_r$, ϑ or ω. The latter can be done by, for example, modifying the lanterns.

The results of fig. 5 can be expressed in the formula [6]):

$$E_b = 7.5\, \bar{L}_r^{2/3}\, \vartheta^{4/3}\, \omega^{2/5},$$

where E_b is in lux, $\bar{L}_r$ in cd/m², ϑ in degrees and ω in steradians.

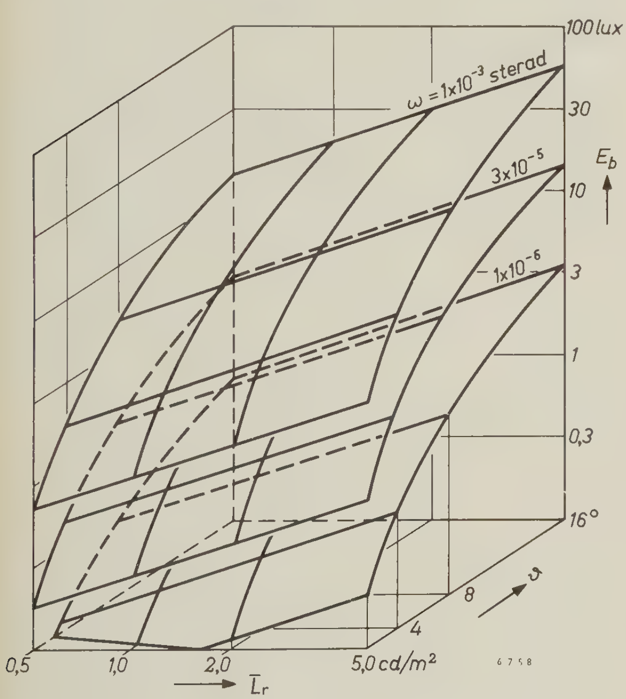
In practice, glare is invariably caused by more than one light source at the same time. Observations have shown that in this case the question whether the degree of visual comfort is still satisfactory can be answered as follows. The quotient of the real illumination on the eye and the maximum admissible value calculated from the above formula is determined for each light source separately. If the sum of these quotients over all light sources is smaller than 1, the degree of visual comfort will be satisfactory from the point of view of glare. Given K light sources, this condition may be expressed mathematically as:

$$\sum_{k=1}^{K} E_k/E_{bk} \leq 1.$$

Here E_k and E_{bk} are respectively the real illumination and the maximum permissible illumination on the eye due to the kth light source. The recommendation, then, is that this condition must be fulfilled wherever the observer may be on the road. It appears that this condition is amply fulfilled in practice if the light emission at angles greater than 80° with the downward vertical is limited to a few tens of candela per thousand lumen, and where at the same time the direction in which the luminous intensity is maximum makes an angle of no more than 70 to 75° with this vertical.

Uniformity of road-surface luminance (patchiness)

Alternate bright and dark patches on the road surface are unavoidable to a certain extent. Like glare, a patchy luminance pattern adversely affects perceptibility, but even before its influence is measurable it has already become unacceptable from the point of view of visual comfort. Thus visual comfort is again the decisive factor. There has not yet been much research on this point.



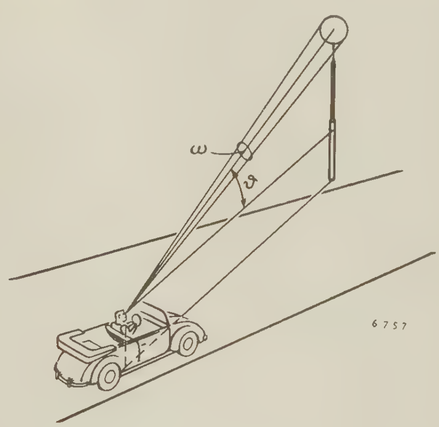


Fig. 5. The illumination E_b produced by a single light source on the eye of an observer, and corresponding to "satisfactory" visual comfort, as a function of the average road-surface luminance $\bar{L}_r$ and the angle ϑ, for three values of the solid angle ω (see sketch).

The recommendations on public lighting issued by the Nederlandse Stichting voor Verlichtingskunde (Netherlands Illuminating Engineering Society) [7]) state that the road-surface luminance in the transverse direction should not vary by more than a factor

[7]) Recommendations for public lighting, published in 1959 by the Nederlandse Stichting voor Verlichtingskunde, Arnhem, Netherlands.

of three, and that moreover the minimum value should not be smaller than one third of the average value. This is a provisional recommendation which at least provides some measure of certainty in regard to perceptibility, and hence to traffic safety. As far as visual comfort is concerned, a road showing the unevenness of surface luminance laid down as maximum in this recommendation would not be acceptable.

A particular problem is the considerable difference between the reflecting properties of a road surface in dry and wet condition. When the road surface is wet it is difficult even to meet the moderate requirements of the provisional recommendation.

Light sources employed

The kinds of light source nowadays used for road lighting — tungsten-filament lamps, sodium lamps, high-pressure mercury-vapour lamps and fluorescent lamps — comprise altogether more than fifty different types of lamp. (This does not include sporadically used types, and no distinction is made between tungsten lamps for different mains voltage but of equivalent wattage.)

Table I gives an idea of the relative extent to which the four kinds of light source are employed. Exact figures are rather difficult to come by. The data on which the table is based were provided by officials responsible for public lighting in various regions or large towns. The wide use still made of tungsten lamps is particularly striking. This appears not only from the preponderance in number and wattage, but also from the luminous-flux figures, which offer a better yardstick for comparison.

Table I. Data on the use of tungsten lamps (G), sodium lamps (S), high-pressure mercury-vapour lamps (M) and fluorescent tubular lamps (F) for road lighting in various countries.

		Netherlands	West Germany	France	Great Britain
Number (%)	G	57	24	77	65
	S	5	1	1	17
	M	9	21	15	15.5
	F	29	54	7	2.5
Luminous flux (%)	G	51	16	48	41
	S	17	2.5	3.5	37
	M	20	29	40	20
	F	12	52.5	8.5	2
Wattage (%)	G	78	38	73.5	63.5
	S	5	1.5	1.5	18
	M	10	27.5	21.5	17
	F	7	33	3.5	1.5

Influence of the kind of light used

The various kinds of light source differ considerably in the spectral composition of the light which they emit, as appears for example in the colour of the light and the colour rendering. As regards high-pressure mercury-vapour lamps a distinction must be made between those having a fluorescent bulb (referred to here as HPL lamps), and those having a clear bulb (referred to here as HP lamps). In Europe (apart from Great Britain) the latter are very seldom used for road lighting. In our view rightly so, since the colour rendering of HP lamps is poor. It was for this reason that HPL lamps were developed, the colour rendering being greatly improved by the light which the fluorescent bulb adds to the mercury light. Sodium lamps too have the disadvantage of poor colour rendering, but in their case, as opposed to HP lamps, this is offset by substantial advantages. We shall return to this point later. The high-pressure mercury lamps used in our investigation were exclusively HPL types.

As regards the tubular fluorescent lamps we have a type in mind which is suitable for public lighting and is known in professional parlance as "white". This type was developed primarily to give a high specific luminous flux rather than ideal colour rendering. In our experiments the main emphasis has been on sodium lamps and HPL lamps, which are the most important for traffic-route lighting. It is of interest to consider the extent to which the spectral composition of the light affects the requirements which, both as regards perceptibility and visual comfort, should be imposed on the average road-surface luminance, the admissible glare and the uniformity of the road-surface luminance. Our considerations are based partly on laboratory experiments carried out indoors under conditions differing considerably from those encountered in practice. Such experiments are nevertheless very useful for purposes of comparison; they have the great advantage that they can be done in the daytime, irrespective of weather conditions. It is also easier to obtain the required numbers of observers.

Kind of light and average road-surface luminance

As regards perceptibility in connection with the average road-surface luminance, it has already been frequently observed that sodium light is superior to tungsten (incandescent) light [8] [9]. The light from

[8]) W. Arndt, Über das Sehen bei Natriumdampf- und Glühlampenlicht, Das Licht 3, 213-215, 1933.

[9]) M. Luckiesh and F. Moss, Seeing in tungsten, mercury and sodium light, Trans. Illum. Engng Soc. (America) 1, 655-674, 1936.

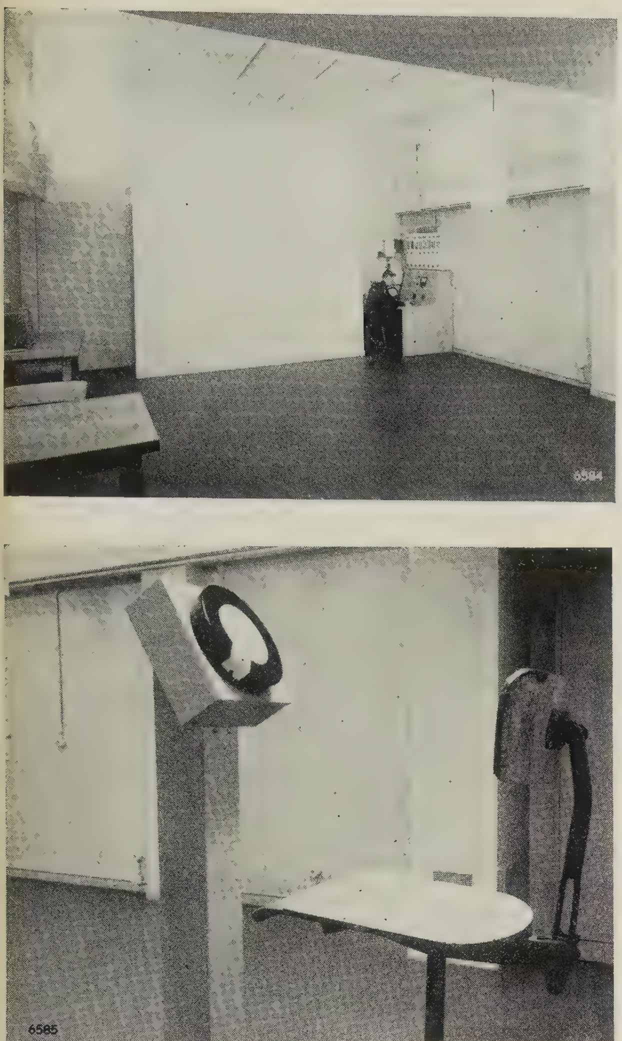


Fig. 6. Two views of the experimental arrangement for comparing the perceptibility of objects under light of different spectral composition. The photo above shows the uniformly illuminated screen, in the middle of which an interchangeable Landolt ring was presented to view for 0.1 sec. Rings of different size and different reflection coefficients were used. The observer had a Landolt ring in front of him (photo below) whose position he had to adjust in accordance with what he had seen or believed he had seen on the screen.

HP lamps was also compared years ago with sodium light. Bouma [10]) and Arndt [8]) found, for example, that visual acuity was somewhat greater in HP light than in sodium light. Weigel [11]) on the other hand found scarcely any difference between these two kinds of light. An investigation of this nature usually consists of experiments in which an object is silhouetted against a uniformly lighted background. In Philips Lighting Laboratory an extensive comparative study has been made of sodium and HPL light. *Fig. 6* gives an impression of the experimental set-up. The object was an interchangeable Landolt ring. Whether or not the ring is correctly perceived (i.e. whether or not the orientation of the gap in the ring is correctly recognized) depends on four quantities:

1) the background luminance L_a,
2) the contrast $C = (L_a - L_o)/L_a$, where L_o is the luminance of the object,
3) the size of the ring,
4) the time t available for perception (exposure time), i.e. the time during which the ring is exposed to view.

For the two kinds of light mentioned, threshold measurements were made with a group of 20 observers for a single exposure time of 0.1 sec. The results are presented in *fig. 7* in a three-dimensional graph, the coordinates of which are L_a, C (both

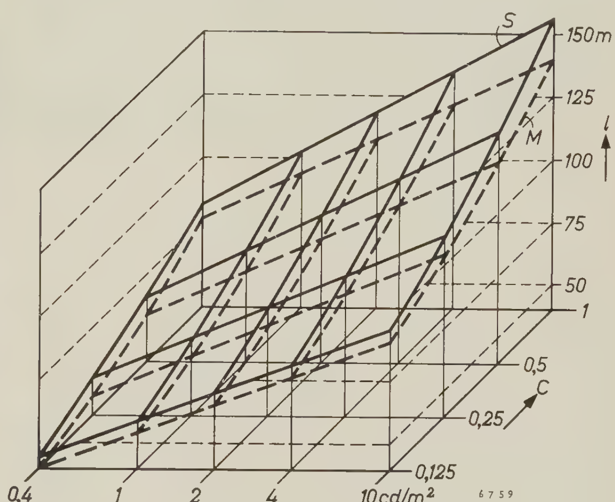


Fig. 7. Distance l at which a Landolt ring of 160 mm diameter is just correctly perceptible, as a function of background luminance L_a and contrast $C = (L_a - L_o)/L_a$ (where L_o is the luminance of the ring) at an exposure time of 0.1 sec, for sodium light (S) and HPL light (M). The distance l was calculated from observations made with the set-up shown in fig. 6, where the distance between observers and object was 6 m.

logarithmic) and the distance l (linear) at which a Landolt ring of 160 mm diameter subtends the same angle as the actual ring. (The latter was situated 6 m away from the observer.) For a given kind of light the region where the (average) observer sees the object correctly when it is exposed to view for t seconds is separated from the region where this is not the case by a plane, called the threshold plane [12]).

---

[10]) P. J. Bouma, Gezichtsscherptemetingen bij diverse lichtsoorten, Ingenieur **49**, A 243-A 246, 1934.

[11]) R. G. Weigel, Untersuchungen über Sehfähigkeit im Natrium- und Quecksilberlicht, insbesondere bei der Strassenbeleuchtung, Das Licht **5**, 211-216, 1935.

[12]) For a different exposure time, different planes are found. The experimental arrangement described was developed by Balder and Fortuin for investigating the influence of the time of observation on the visibility of stationary objects under tungsten light; see J. J. Balder and G. J. Fortuin, Proc. Int. Comm. on Illumination, Zürich 1955, I.

It is seen from the graph that sodium light is more favourable in this respect than HPL light. Analysis of the observations on which the graph is based show that, to find the same threshold value of l at a given contrast (this threshold value is a measure of visual acuity), the background luminance L_a for HPL light must be on an average 54% higher (standard deviation 12%) than for sodium light.

The reciprocal of the threshold value of C is called the contrast sensitivity. The more l decreases, i.e. the larger the object becomes (all details proportionately larger), the closer the threshold planes for the various kinds of light approach each other. For large objects, then, there is no difference between the various kinds of light, either in visual acuity or in contrast sensitivity. Numerous contrast-sensitivity measurements have been reported in the literature which indicate that the kind of light has scarcely any influence on contrast sensitivity. Measurements of this nature always relate to large objects.

Our finding that sodium light gives better perceptibility than HPL light is in good agreement with recent results obtained by Jainski [13]), likewise using Landolt rings but only one contrast value ($C = 0.96$). *Fig. 8* — a cross-section of fig. 7 perpendicular to the C axis at the point $C = 0.96$ — shows in addition to our own results the lines derived from Jainski's observations for sodium, HPL, fluorescent and tungsten light. It was not to be expected that Jainski's lines would coincide with ours, for they relate to another group of observers. His results too, however, reveal the difference between sodium and HPL light, indicating that the background luminance for HPL, fluorescent and tungsten light must be respectively 35, 65 an 100% higher than for sodium light in order to obtain the same visual acuity.

We have also compared sodium and HPL light in regard to perceptibility in actual road conditions. Landolt rings of 160 mm diameter were set up along the road, and the distance was determined at which the rings were still properly perceptible. The difficulty that this distance depends on the position on the road, owing to the road-surface luminance not being uniform, was overcome by distributing large numbers of rings systematically over the road (*fig. 9*). The experiments were done both on ordinary roads and in our outdoor laboratory for road lighting [14]) at Turnhout (where the photograph of fig. 9 was taken). The outdoor laboratory consists of a road provided with mobile trolley-mounted lighting masts on which the lanterns can be adjusted in height and are readily interchangeable. As was to be expected, the results of the tests on ordinary roads showed a greater spread than those in the outdoor laboratory, where the conditions can be much better controlled. In both cases, however, the results correspond to those of the indoor experiments; the differences were only greater [15]).

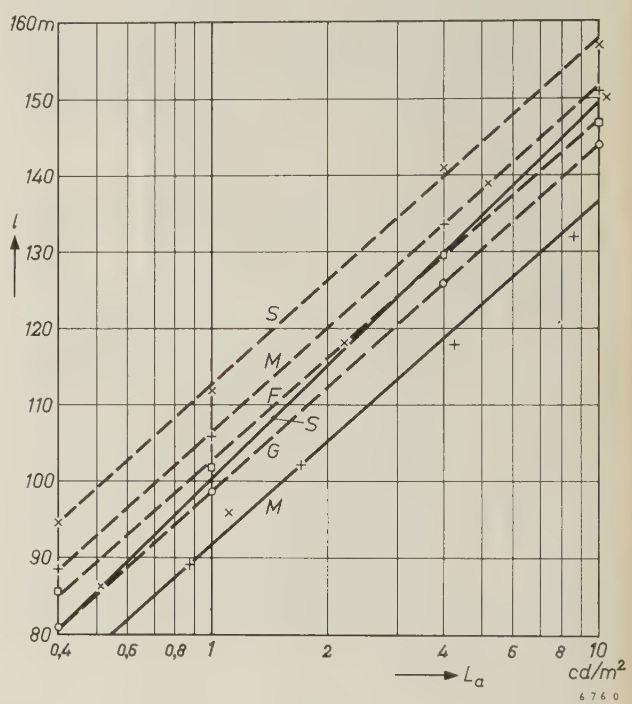


Fig. 8. Cross-section perpendicular to the C axis of fig. 7, at the point $C = 0.96$. The planes S and M from fig. 7 appear in this cross-section as the full lines S and M. For comparison, the broken lines represent the results of Jainski [13]), who compared tungsten light (G), sodium light (S), HPL light (M) and fluorescent light (F) at the same contrast value ($C = 0.96$).

In the following figures the letters G, S, M and F have the same meaning.

As stated on page 263, whether or not an object can be perceived also depends on the time available for perception, the exposure time. There is thus a threshold exposure time corresponding to any given combination of object size, contrast and background luminance. The reciprocal of this time is called the speed of perception. In *fig. 10* the speed of perception is represented as a function of object luminance for a given contrast and size of object, both for sodium and tungsten light [16]). *Fig. 11* gives the speed of

[13]) P. Jainski, Die Sehschärfe des menschlichen Auges bei verschiedenen Lichtarten, Lichttechnik **12**, 402-405, 1960.

[14]) J. Hamming and J. F. T. van Heemskerck Veeckens, An open-air laboratory for road lighting, Philips tech. Rev. **19**, 202-205, 1957/58.

[15]) J. B. de Boer, The application of sodium lamps to public lighting, Illum. Engng **56**, 293-301, 1961 (No. 4).

[16]) P. J. Bouma, Perception on the road when visibility is low, Philips tech. Rev. **9**, 149-157, 1947/48.

Fig. 9. View of Philips outdoor laboratory for road lighting at Turnhout [14]), showing Landolt rings systematically distributed for investigating the influence of the kind of light on perceptibility.

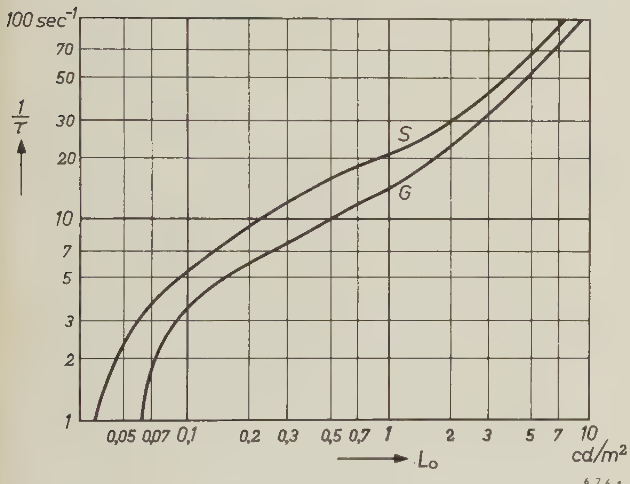


Fig. 10. Speed of perception $1/\tau$ (τ = exposure time) for a stationary object, at a fixed value of contrast, as a function of object luminance L_0 for tungsten light and sodium light, after measurements by Bouma [16]).

To obtain some idea of the influence which the kind of light has on the desired road-surface luminance from the point of view of visual comfort, the results collected in fig. 2 were analysed according to the kinds of light concerned. The considerable spread makes a significant comparison difficult. If

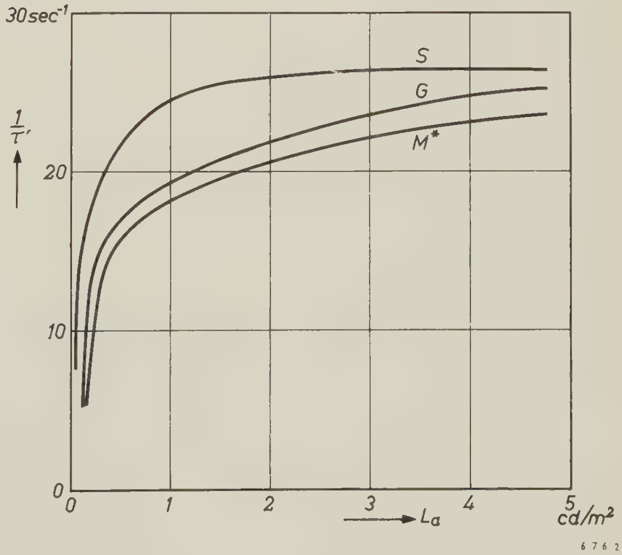


Fig. 11. Speed of perception $1/\tau'$ (τ' = exposure time) for a moving object, at a fixed value of contrast, as a function of background luminance L_a for tungsten light, sodium light and HP light (M*), after measurements by Weigel [11]).

perception for moving objects according to Weigel [11]) for sodium, tungsten and HP light. Similar measurements have also been done by Arndt [8]) and by Luckiesh and Moss [9]). They found that the values of background luminance needed under the different kinds of light in order to arrive at the same speed of perception stand to one another roughly in the ratio of the values needed to achieve the same visual acuity.

we try to represent by straight lines the relation between the average road-surface luminance in the different kinds of light and the subjective evaluation of that luminance, we find lines of different slope. A statistical analysis has shown, however, that these differences of slope are not significant. Our procedure was therefore as follows. In *fig. 12* —

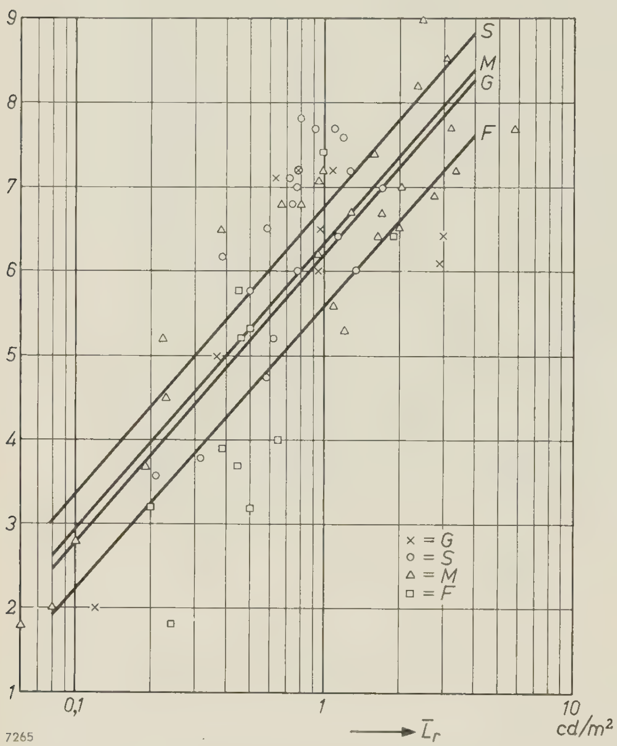


Fig. 12. Average assessments of the lighting level in 70 streets by 16 experts (cf. fig. 2), analysed according to the four kinds of light.

which contains the same points as fig. 2 — we first drew the straight line which, disregarding the kind of light, gives the best approximation to the above-mentioned relation. Parallel with this we then drew lines through the centres of gravity of the clusters of points for the different kinds of light. Interpreting the results in this way it is seen that, in order to obtain the same average subjective evaluation of the road-surface luminance as for sodium light, the average luminance must be increased by 34% for HPL light, by 50% for tungsten light and by 125% for fluorescent light. In other words, given the same road-surface luminance, sodium light creates an impression of greater brightness. The standard deviations of the above percentages are 21, 28 and 45%, respectively.

It should be added that the high value of 125% for fluorescent light is probably attributable in part to the lanterns used, which did not give a cut-off light distribution and therefore caused fairly strong glare. The lanterns for the other three kinds of light were all of the cut-off type. The result of this comparison of sodium and HPL light with respect to road-surface luminance shows the same trend as found by Stevens and Ferguson [17]) who compared sodium with HP light in a range of luminances usual for artificially lighted road surfaces.

Kind of light and glare

On the subject of glare we have already seen that the extent to which glare is admissible is determined by the visual discomfort it causes and not by perceptibility. For the purpose of comparing the discomfort glare caused by light of various kinds (tungsten light, sodium light, HPL light and fluorescent light) we used, among other things, a simulated street-lighting installation in our laboratory indoors [18]). This made it possible to vary separately the kind of light used, the brightness of the sources and the average road-surface luminance. All other factors that might affect the degree of discomfort, such as the size and situation of the light sources, and the luminance distribution of source and road surface, were kept constant.

For the four kinds of light concerned, *fig. 13* shows the luminance L_l of the light sources which is still just admissible, according to the average evaluation of six observers, as a function of the average road-surface luminance $\bar{L}_r$. It appears that, in the interval of $\bar{L}_r$ investigated (0.1 to 10 cd/m²),

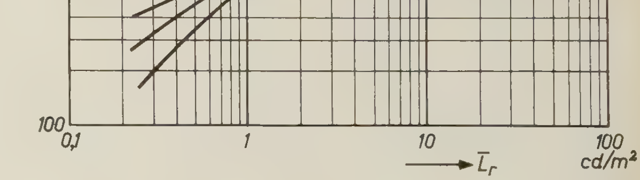


Fig. 13. Just-admissible luminance L_l of the lanterns for the four kinds of light source in a street-lighting installation, as a function of the average road-surface luminance $\bar{L}_r$, according to the average evaluation of a group of six observers.

[17]) H. M. Ferguson and W. R. Stevens, Relative brightness of coloured light sources, Trans. Illum. Engng Soc. (London) **21**, 227-247, 1956.

[18]) For a description of the experimental arrangement, see J. B. de Boer and J. F. T. van Heemskerck Veeckens, Observations on discomfort glare in street lighting. Influence of the colour of the light, Proc. Int. Comm. on Illumination, Zürich 1955.

visual comfort with sodium lighting is still found to be satisfactory at considerably higher light-source luminances than with the other three kinds of light.

Sodium, HPL and fluorescent light were again compared at one value of $\bar{L}_r$ (1 cd/m^2) by a larger group of observers (50 persons). The result found was that, for the same discomfort glare, the light-source luminance with sodium lighting may permissibly be 30% greater than with fluorescent lighting and 45% greater than with HPL lighting, in agreement with fig. 13. Ferguson, Reeves and Stevens, who compared sodium with HP lighting [17][19]), also concluded that the light-source luminance may be greater with sodium light than with mercury light.

We tested these conclusions against the results of the evaluation by the 16 experienced observers of discomfort glare in the 70 streets mentioned earlier (page 259). When these evaluations are analysed according to the kind of light used, it is found here too that sodium light sources may permissibly have a considerably higher luminance than other kinds of light sources.

The influence which the colour of the light has on the extent to which glare impairs perceptibility is of less importance, since the admissible glare is governed by the visual discomfort caused. It may be added for completeness, however, that the colour of the light is found to have scarcely any influence in this connection.

A further point of importance is the effect of the colour of the light on the time taken to recover from glare. We have found that, given otherwise identical conditions, the recovery time in the case of sodium light is only three-quarters of that in the case of HPL light and two-thirds of that for tungsten light [20]).

Kind of light and patchiness of luminance pattern

As regards patchy or irregular luminance patterns on the road surface the decisive factor, as with glare, is visual comfort. Investigations in this field are still in the initial stages: the following comparative experiments with sodium and HPL light, done in the outdoor laboratory, represent a first attempt to place the problem of non-uniform road luminance on a quantitative basis.

The average road-surface luminance $\bar{L}_r$ and the degree of patchiness were systematically varied. A group of 25 observers was asked to assess visual comfort in regard to the patchiness of the luminance pattern with one of the ratings: bad, inadequate, fair, good or excellent. For the purpose of averaging, the numbers 1, 3, 5, 7 and 9 were assigned to the respective ratings. The patchiness of the luminance pattern — the measure of which was taken to be the ratio R between the maximum and minimum road luminance — was varied by altering the height of the lanterns. Lanterns giving the same light distribution were used for both kinds of light so that the distribution of luminance on the road surface is in both cases identical for the same value of R. *Fig. 14* shows the average evaluation of the observers as a function of $\bar{L}_r$ for sodium and HPL light and for various values of R. The following two conclusions seem to be warranted:

1) Stronger local variations in road-surface luminance are acceptable the higher is the average value of that luminance.
2) Under sodium light, other conditions being identical, stronger local variations in road-surface luminance are permissible than under HPL light.

These conclusions have been confirmed in broad lines by subsequent experiments. Further investigation is needed before quantitative pronouncements can be made.

Summarizing, it can be said that investigations into the influence of the kind of light used have demonstrated that sodium light offers the following marked advantages over the other kinds of light considered,

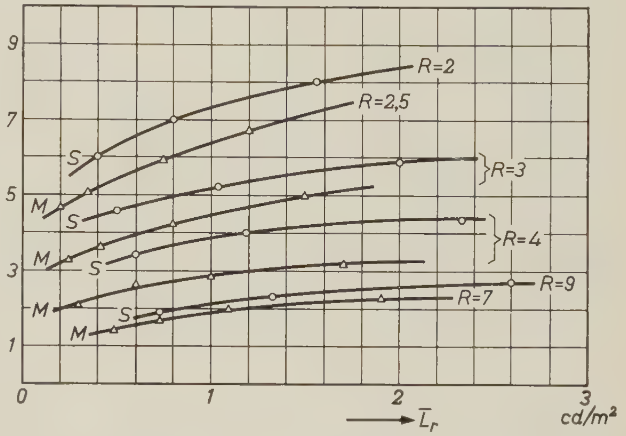


Fig. 14. Evaluation of the uniformity of road-surface luminance in outdoor laboratory experiments as a function of average road-surface luminance $\bar{L}_r$, for various values of the ratio R between the maximum and minimum road-surface luminance. The numbers 1, 3, 5, 7 and 9 correspond to the ratings bad, inadequate, fair, good and excellent.

[19]) H. M. Ferguson, J. Reeves and W. R. Stevens, A note on the relative discomfort glare from mercury, sodium and tungsten light sources, G. E. C. Journal **20**, 184-187, 1953.

[20]) J. B. de Boer, La couleur de la lumière dans l'éclairage pour la circulation routière, Lux, 1959, pp. 20-25 (No. 1), and pp. 46-50 (No. 2).

1) Greater visual acuity. With other kinds of light the average road-surface luminance must be about 1.5 times higher to give the same visual acuity. (This does not apply to a comparison with HP light; see page 263.)
2) For the same road-surface luminance, sodium light gives an impression of greater brightness. In that respect sodium light is more than 30% superior to HPL light, which takes second place.
3) Greater speed of perception. The data at present available suggest that, in this respect, the various kinds of light stand in roughly the same ratio to one another as in regard to visual acuity.
4) Less discomfort glare. As a result, the luminances of the light sources themselves can be about 1.4 times higher than for other kinds of light under otherwise identical conditions.
5) Patchiness of the road-surface luminance pattern is less disturbing under sodium lighting.

It follows from this that, for a lighting installation of a given quality, the use of sodium lamps requires only about 75% of the lumens needed from other light sources. This, combined with the very high luminous efficiency of sodium lamps, makes sodium lighting very attractive from the economic point of view.

Practical value of good visual acuity

It is sometimes doubted whether better visual acuity under a particular kind of light is an advantage for the purposes of road lighting. Visual acuity, it is argued, is of minor importance because perception in practice depends on seeing contrasts in the luminance of relatively large objects. It is therefore reasoned that perceptibility on the road is governed by the contrast sensitivity in respect of large objects, which is not, as we have seen (page 264), significantly affected by the kind of light used.

This opinion is understandable if related to the conditions that existed some twenty years ago, when levels of a few tenths of a cd/m^2 were common even on important traffic routes. At such levels it is indeed true that perception depends on seeing large objects as dark silhouettes against the road surface. Details of the objects are not then perceptible. In the busy traffic of today this is definitely an unsatisfactory standard of perceptibility. It is precisely the perception of details that leads to immediate recognition and to the decision as to whether the object calls for further attention or not. It is important, for example, that a motorist should be able, at night just as in the daytime, to see whether a pedestrian standing on the kerb has noticed him. If so, the motorist need pay no further special attention to that pedestrian. Every gain in visual acuity thus contributes to greater safety on the roads.

Importance of dimensions, shape and luminance of light sources

A high and uniform luminance on the road surface imposes certain demands on the distribution of light from a street lantern. The light distribution required in a vertical plane parallel to the axis of the road is usually of the type shown in *fig. 15.*

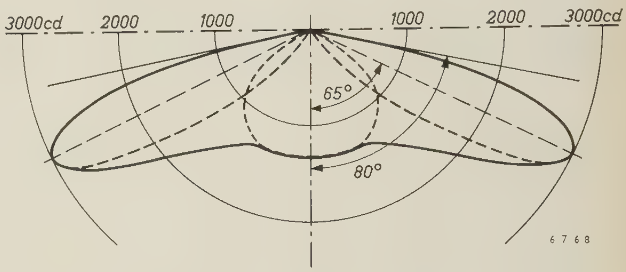


Fig. 15. Example of the distribution of light from a street lantern as required in the vertical plane parallel to the axis of the road. A distribution of this kind can be obtained with the aid of two mirrors, each of which produces one of the narrow beams represented by dotted lines. Together with the remainder of the light, including the direct light from the lamp — the third dotted curve — they provide the distribution required. The luminous intensities given in candelas are normal for a lantern fitted with lamps giving a total light output of about 10 000 lm.

The wide spread in this plane, i.e. in the longitudinal direction of the road, is needed in order to bridge the distance between two successive lanterns. A certain lateral spread is also needed in order to span the width of the road. Excessive lateral spread, however, means a loss of useful light on the road. The extent to which the requirements can be met by reasonable optical means depends on the dimensions, shape and luminance of the light sources. In these respects the four kinds of light source treated in this article show considerable differences. *Table II* gives a survey of these quantities for various types of lamp in each category. If we compare lamps in this table that have roughly the same luminous flux, we notice that tungsten lamps are the most concentrated light sources (highest luminance and hence smallest dimensions of radiating portion), whilst fluorescent lamps with their low luminance and great length represent the other extreme. HPL and sodium lamps have virtually the same luminance, but differ considerably in shape.

To give an example illustrating the significance of dimensions, shape and luminance, we assume that we have to design for each of the four kinds of light source a system of reflectors giving a longitudinal distribution as in fig. 15. The values of luminous

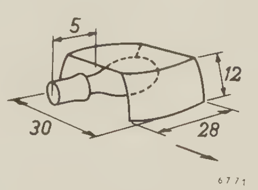
Table II. Luminous flux, luminance and dimensions of the radiating portion of various types of lamps in the four categories dealt with in this article. The depreciation (average luminous flux over whole life divided by the luminous flux after 100 hours) is also shown. The dimensions given for the radiating portion have the following meanings. For the tungsten lamps: length, breadth and height of an imaginary rectangular parallelepiped enclosing the filament; for the sodium lamps: length and diameter of the almost contiguous limbs of the U-shaped discharge tube; for the HPL lamps: length and diameter of the ovoid fluorescent part of the bulb; for the "TL" lamps: length and diameter of the fluorescent part of the tube. (1 cd/cm² = 2920 footlambert.)

Kind of light source	Type designation	Rated power	Luminous flux at half life	Luminance at half life	Dimensions of radiating portion	Depreciation
		watts	lm	cd/cm²	cm	
Tungsten lamp (220 V)	GLS clear	100	1330	600	2.5 1 0.07	0.96
		500	9000	800	3.5 2.5 0.09	0.95
		1500	27600	1000	4 2 2.5	0.92
Sodium lamp	SOI	45	3100	10	14 1.2	0.94
		60	4700	10	20 1.2	0.94
		85	7500	10	30 1.3	0.94
		140	12000	12	40 1.6	0.94
		200	20200	14	66 1.6	0.94
High-pressure mercury-vapour lamp with fluorescent bulb	HPL	80	2700	10	11 7	0.90
		125	4850	10	12 7.5	0.90
		250	10500	15	15 9	0.90
		400	18000	15	19 12	0.90
		700	33000	15	23 14	0.87
		1000	45200	15	26 16.5	0.87
Tubular fluorescent lamp	"TL" 33	20	1080	0.60	57 3.8	0.87
		40	2430	0.65	117 3.8	0.87
		65	4400	0.8	148 3.8	0.80
		125	5500	1.1	148 3.5	0.80

intensity specified in fig. 15 are normal for a lantern containing a light source of about 10 000 lumens. (The value of 10 000 lumens was chosen because it can be achieved with all four kinds of light source.) Since the largest fluorescent lamp at present used for road lighting in Europe delivers only about 5500 lumens, two lamps have to be used in this case in each lantern. *Fig. 16* shows sketches of four designs that meet the requirements. For simplicity, the reflectors are considered to be symmetrical with respect to the vertical plane parallel to the axis of the road, i.e. the plane to which the specified light distribution applies. As we shall see below, the shape and size of the light source do play a considerable part in determining the design of the reflector.

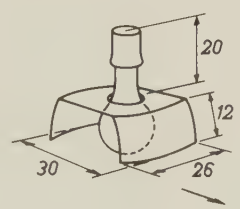
The desired longitudinal distribution of the light can be obtained by means of two mirrors, each of which

M



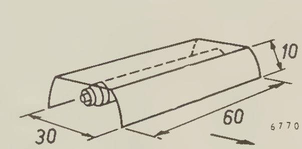
HPL 250 W; 10 500 lm; 15 cd/cm²; main dimensions 22 and 9 cm; ovoid radiating portion 15 × 9 cm.

G



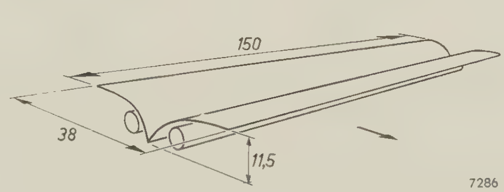
Clear-bulb tungsten lamp 500 W; 9000 lm; 800 cd/cm²; main dimensions 28 and 13 cm; filament 1 mm thick, bent to a not entirely closed circle 3.5 cm in diameter.

S



SO 140 W; 12 000 lm; 12 cd/cm²; main dimensions 52 and 6 cm; radiating portion is a U-tube with the limbs almost touching; length of limbs 40 cm, diameter 1.6 cm.

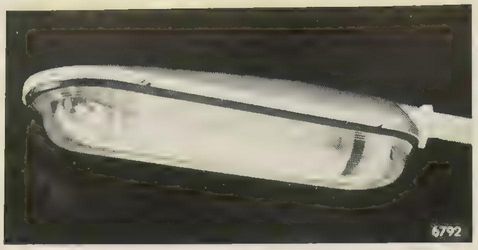
F



"TL" 125 W; 2× 5500 lm; 1.1 cd/cm²; main dimensions 151 and 3.5 cm; radiating portion cylindrical, length 148 cm, diameter 3.5 cm.

Fig. 16. Design sketches, for each of the four kinds of light source, of mirrors — and their position relative to the lamps — for producing in the vertical plane parallel to the axis of the road a light distribution approaching that shown in fig. 15. The flat surfaces above the lamps give diffuse reflection. The principal data of the lamps are given beside the sketches; the values of luminous flux and luminance mentioned hold at the half life of the lamp. The arrows indicate the direction of the road.

a



b

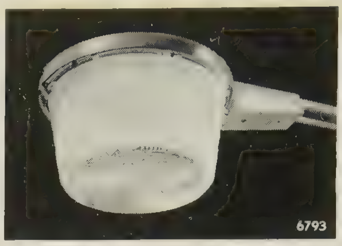
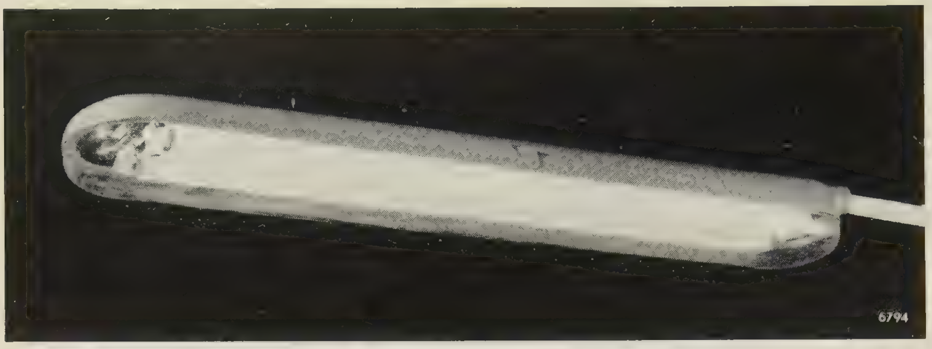


Fig. 17. Three examples of modern enclosed street lanterns; *a*) for a sodium lamp of 200 W (20 200 lm); *b*) for an HPL lamp of 400 W (18 000 lm); *c*) for two fluorescent "TL" lamps of 125 W (2 × 5500 lm). The lanterns are reproduced on the same scale; the overall length of the lantern for the "TL" lamps is 1.8 m.

c



gives a narrow beam at a wide angle with the vertical. With the direct light and the light reflected from the top of the lantern, the two beams produce roughly the distribution required (see the dotted curves in fig. 15). In the transverse direction of the road less pronounced beaming is required. It is a general rule that, in order to produce a specific beam in a given plane, a larger reflector is needed the larger are the dimensions of the light source in that plane. Since the strongest beaming is required in the vertical plane parallel to the axis of the road, the lamps are mounted so that their smallest dimensions fall in that plane. The smallest dimension of the HPL lamp is still a good 9 cm, and therefore this type of lamp constitutes the most difficult problem in regard to beaming the light in the vertical plane parallel to the axis of the road. It was found, however, that the requirement can be fulfilled by using a simple mirror (part of a paraboloid of revolution) of the dimensions given in fig. 16. Since the largest dimension is decisive in this arrangement as regards the transverse beaming, the lateral spread in this case is automatically greater; its value is found, however, to be acceptable.

The mirror for the tungsten lamp is designed so as to produce the same light distribution as the HPL lamp, both along the road and across it. The light source (filament) being so much smaller, the light distribution can be well controlled. The small dimensions of the light source are not, however, purely an advantage. In order to obtain the required beaming, longitudinally and laterally, it is necessary to give the mirror (fig. 16) a different radius of curvature in two mutually perpendicular directions. Moreover, high demands are made on the reflecting surface, since with a concentrated light source any irregularity in the mirror shows up as a patch of different brightness on the road. Where this is the case, other optical aids have to be enlisted, for example a simple mirror which gives good longitudinal beaming, combined with a ribbed cover of transparent material, which provides the necessary lateral spread and blurs any irregularities. A concentrated light source thus calls for a lantern which, although usually small, is fairly complicated in construction.

Fluorescent lamps create no difficulties as far as longitudinal beaming is concerned, but their length precludes any possibility of lateral beaming.

With sodium lamps the light distribution along the road is no problem either. Some lateral beaming is possible owing to the fact that the distance between the lamp and the mirror can be given a value comparable in some measure to the length of the lamp. Sodium and HPL lamps are roughly equivalent in regard to the control of the light distribution: with sodium lamps the lateral distribution is less easy to control, whereas with HPL lamps it is rather more difficult to achieve a completely satisfactory distribution in the longitudinal direction.

It is by no means the rule that street-lighting lanterns are equipped with mirrors. *Fig. 17* shows three examples where this is not the case. It is noticeable that the fluorescent-lamp lantern, although by far the biggest, gives the least light. Moreover it contains no provisions for beaming the

light, a function which is fulfilled in the other lanterns by the prismatic ribbing in the transparent covers. To obtain effective beaming from the fluorescent-lamp lantern it would have to be made very much wider and larger. This indicates that fluorescent lamps are really not so suitable for lighting traffic routes. For HPL or sodium lamps, lanterns can be designed that are more easily manageable and more acceptable from the aesthetic point of view.

In this connection some remarks may be made on HP lamps, i.e. high-pressure mercury-vapour lamps of the clear-bulb type. These lamps have a concentrated radiating portion and are therefore in the same position as tungsten lamps in regard to the control of their light distribution. Good control is thus possible with lanterns of modest dimensions, though of somewhat complicated design. The lanterns for HP lamps can be designed more readily than for HPL and sodium lamps to give very wide-angled distribution, with the maximum luminous intensity almost horizontal (cf. fig. 15), and this has the advantage of allowing wider spacing between the poles. In countries where such light distributions are still preferred HP lamps are therefore in fairly common use. But apart from the growing recognition that such wide-angle lanterns are undesirable from the point of view of discomfort glare, there is another reason why HP lamps are more and more being superseded by sodium and HPL lamps. There is a trend in road engineering to make surfaces rougher, thereby giving more diffuse reflection. The aim is to reduce the difference in appearance between wet and dry surfaces, and also to reduce the hazard of skidding. On more diffusely reflecting road surfaces there is not much point in using these wide-angle lanterns, since in this case the light emitted at angles near the horizontal contributes very little to the luminance of the road. That being so, sodium lamps are preferable on traffic routes where colour rendering is a minor consideration, for HP light and sodium light — both of which give poor colour rendering — are only comparable as far as visual acuity is concerned. In other respects (glare, required surface luminance, speed of perception) HP light is inferior to sodium light. In cases where colour rendering *is* important, for instance on main roads in built-up areas, in shopping centres or city squares, HPL light is greatly to be preferred.

Temperature and voltage variations

If the luminous flux of the four kinds of light source be measured indoors as a function of the ambient temperature (the latter being measured at

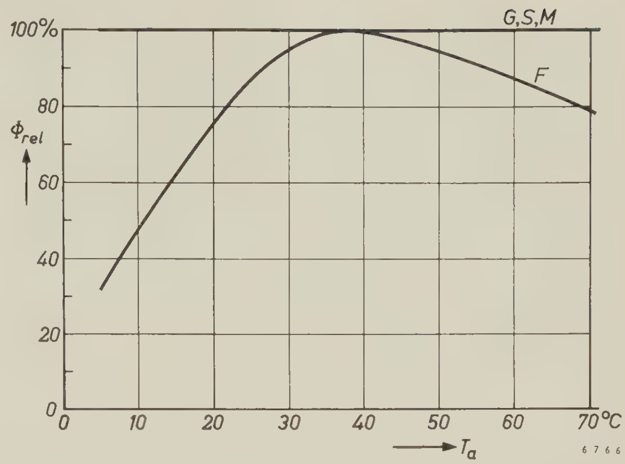


Fig. 18. Relative luminous flux Φ_{rel} as a function of ambient temperature T_a, for the four kinds of light source.

great distance from the lamp), curves roughly resembling that shown in *fig. 18* are found. In the case of fluorescent lamps this dependence is such that it must be taken into account in the design of the lantern. The design must provide for optimum light output in the most common range of night-time temperatures (in our latitudes between 0 and 10 °C). Under other conditions, e.g. during cold winter nights, the light output may then be appreciably lower. This is a disadvantage of fluorescent lamps compared with the three other light sources.

The light output from all four kinds of light source is dependent on the supply voltage (*fig. 19*). In that respect sodium lamps are the most favourable. This is fortunate, since the principal application of these

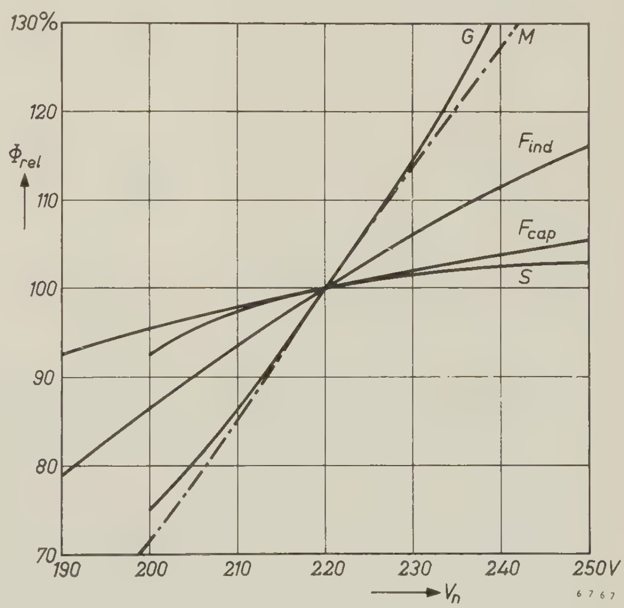


Fig. 19. Relative luminous flux Φ_{rel} as a function of mains voltage V_n for the four kinds of light source. For the fluorescent lamps a distinction must be made between operation with a capacitive ballast (F_{cap}) and with an inductive ballast (F_{ind}).

lamps is on roads outside the built-up areas, where they are usually connected to branch lines of the electric mains and thus exposed to the worst voltage fluctuations. The relative insensitivity of sodium lamps to voltage fluctuations means that the voltage fluctuations along the supply cables may be larger while the difference in luminous flux between the various lamps fed by a given cable will still be within the prescribed limits. It is therefore possible to cut cable costs by reducing the copper cross-sections of the cables.

It is evident from the foregoing that, for lighting traffic routes, sodium lamps deserve preference over other light sources in all cases where colour rendering is a minor consideration. Sodium light offers better visibility and more visual comfort than other kinds of light. Moreover sodium lamps possess properties that make them particularly attractive for large lighting installations: they have a high luminous efficiency, making economic operation possible; their shape and dimensions facilitate the optical design of street lanterns; and they are relatively little affected by temperature and voltage fluctuations. Where their poor colour rendering is an insuperable objection, high-pressure mercury lamps with fluorescent bulbs (HPL lamps) are preferable to fluorescent and tungsten lamps, chiefly because they can supply a much higher luminous flux, and also because — compared with fluorescent lamps — their shape and dimensions are more advantageous and they are less sensitive to temperature variations.

Summary. If a traffic route is to be lighted so that motorized vehicles can proceed safely without using headlights, the lighting installation must create conditions that offer acceptable visual comfort and perceptibility. The extent to which it does so is determined by the average luminance of the road surface, the glare caused by the lanterns of the installation and the uniformity of the surface luminance. Experiments in Philips' lighting laboratories, and elsewhere, indicate that 2 cd/m^2 (0.6 footlambert) is a reasonable average road-surface luminance. A recommendation is made as to what constitutes admissible glare; the effects of irregular surface luminance (bright and dark patches) have not yet been sufficiently investigated for a recommendation to be given.

Four commonly used kinds of light source — tungsten lamps, sodium lamps, high-pressure mercury lamps with fluorescent bulbs (HPL lamps) and tubular fluorescent lamps — are compared in regard to the influence of the kind of light on visual comfort and perceptibility, to the significance of their dimensions, shape and luminance, and to their sensitivity to temperature and voltage fluctuations. Sodium lamps compare favourably on all counts. The conclusion is that, where their poor colour rendering is a minor consideration, sodium lamps deserve preference for road lighting. Where colour discrimination is important, the use of HPL lamps is recommended.

DC/AC CONVERTERS USING SILICON CONTROLLED RECTIFIERS FOR FLUORESCENT LIGHTING

by J. J. WILTING *).

621.314.57:621.314.63:621.327.534.15

In lighting practice today there is a general trend towards higher levels of illumination. The lighting in public transport vehicles, such as railway carriages and buses, is no exception. The power in these vehicles is usually obtained from a dynamo of limited capacity, together with a buffer battery. It is therefore necessary to use very economical light sources, for which purpose tubular fluorescent lamps are particularly suitable.

Since the power source delivers direct current, two systems are possible:

1) Special fluorescent lamps may be used (e.g. Philips "TL" C type) which are fed in series with a ballast resistor directly from the DC source [1]). This system is restricted to voltages of at least 72 V.
2) Standard fluorescent lamps may be used in conjunction with a DC/AC converter.

The second system has the advantage over the first that the loss in the ballasts is very much lower. The converters originally used were almost invariably robust rotary types, like centrifugal converters employing a rotating mercury jet [1]). Nowadays electronic converters are gaining ground as a result of the development of semiconductor devices, such as the transistor [2]) and the silicon controlled rectifier.

The electrical behaviour of the silicon controlled rectifier resembles that of thyratrons and ignitrons, hence the name "solid-state thyratron" by which it is sometimes known [3]). Compared with these two

*) Philips Lighting Division, Eindhoven.

[1]) L. P. M. ten Dam and D. Kolkman, Lighting in trains and other transport vehicles with fluorescent lamps, Philips tech. Rev. **18**, 11-18, 1956/57.

[2]) T. Hehenkamp and J. J. Wilting, Transistor D.C. converters for fluorescent-lamp power supplies, Philips tech. Rev. **20**, 362-366, 1958/59.

[3]) F. W. Gutzwiller, Phase-controlling kilowatts with silicon semiconductors, Control Engng **6**, 113-119, 1959. — This rectifier is available commercially under various names, such as SCR (silicon controlled rectifier), "Thyristor" and "Trinistor". The I.E.C. recently recommended the general name "pylistor" (Interlaken, June 1961; see Bull. Schweizer Elektrot. Ver. **52**, 934, 1961). This name is derived from $\pi\upsilon\lambda\eta$ = gate, which is roughly synonymous with $\vartheta\upsilon\varrho\alpha$ = door, from which the names thyratron and "Thyristor" were formed.

electronic switching or commutating devices — to which we may add the triode — the silicon controlled rectifier has the advantage of a much smaller voltage loss (only 1 to 1.5 V) and consequently a higher efficiency. It is particularly compact and rugged and requires no heating of the cathode. Although its switching speed is lower than that of a triode, it is greater than that of a thyratron or ignitron. The maximum permissible voltage is at present lower than for thyratrons and ignitrons but much higher than for transistors. Silicon controlled rectifiers are now commercially available [4]) for operation at a rated peak voltage of 400 V and a mean current of 70 A, and can be used for building converters for tens of kilowatts. It has been reported [5]) that further development is expected to raise these values to 1000 V and 1000 A, giving a power-handling rating of 1 MW per rectifier.

Silicon controlled rectifiers are still very expensive. Even so, as an investment for a lighting installation converters using these devices are already comparable with rotary converters, and are expected to compare even more favourably in the near future. Among their present advantages are their considerably higher efficiency, their smaller weight and volume, and the fact that they need no maintenance.

Advantages of operating fluorescent lamps from a converter

In the conversion of direct current into alternating current the choice of voltage and frequency is fairly wide. Where converters for fluorescent lighting are concerned, the voltage and frequency of the AC mains should preferably not be chosen, for neither have the optimum value for operating fluorescent lamps. A voltage of 220 V, for example, is inadequate for reliably starting long fluorescent lamps (types of 40 W and more) unless special measures have been taken, and at the usual low frequencies of 50 and 60 c/s the lamps are far from operating under the most favourable conditions. We shall now discuss both points briefly.

Most fluorescent lamps work in conjunction with a ballast and a starter, which delivers a high (and usually brief) voltage surge sufficient to initiate the discharge. Moreover, the electrodes of the lamp are preheated, which lowers the ignition voltage required. As a result, the ignition is always attended by some delay. In one type of lamp — Philips "TL" S lamp [6]) — a conducting strip on the inside of the tube has so reduced the ignition voltage as to make the above measures unnecessary. This lamp is of course somewhat dearer in construction than a conventional fluorescent lamp, and the losses in the strip make the efficiency somewhat lower.

Using a converter the voltage can be chosen high enough to ignite the longest lamps reliably and without delay with a simple ballast. Preheating is unnecessary (the electrodes must then be accordingly dimensioned) and no conducting strip is needed. To comply with safety regulations the secondary of the transformer in the converter can be centrally earthed, so that the AC cables carry half the full potential with respect to earth.

As regards the frequency, there are several advantages in raising its value to between 5 and 10 kc/s for fluorescent lamps:

1) The weight and size of the ballasts, and the ballast losses, can be considerably reduced. Light weight and low heat generation are sometimes of decisive importance.
2) The luminous efficiency of fluorescent lamps rises with increasing frequency [2]) [7]). The efficiency of a 40 W "TL" lamp, for example, is about 10% higher between 5 and 10 kc/s than at 50 c/s.
3) The light is steadier, without any stroboscopic effect.
4) The lamps cause less radio interference.

The latter two advantages are due to the fact that at high frequencies the gas discharge is much more regular than at the usual mains frequencies [8]): the ion concentration remains virtually constant, re-ignition effects are eliminated. This may also be assumed to benefit the life of the lamp, but life tests still have to confirm this assumption. (The choice of frequencies higher than 10 kc/s does not add much to the above-mentioned advantages, whereas it considerably increases the losses, including radiation losses, entailing the risk of interfering with communication channels.)

The conspicuous benefits of high frequencies are a strong argument in favour of using converters that deliver alternating current at these frequencies. The transistor converter is capable of doing so [2]), but because of its low power and the inability of transistors to withstand high voltages, its applications are very limited (lighting in buses etc.). The con-

[4]) See e.g. Controlled-rectifier manual of the (American) General Electric Co.
[5]) E. J. Duckett, DC to AC power conversion by semiconductor converters, Westinghouse Engr **20**, 170-174, 1960 (No. 6).
[6]) W. Elenbaas and T. Holmes, An instant-starting fluorescent lamp in series with an incandescent lamp, Philips tech. Rev. **12**, 129-135, 1950/51.
[7]) J. H. Campbell, New parameters for high-frequency lighting systems, Illum. Engng **55**, 247-256, 1960 (No. 5).
[8]) Fluorescent lamps and lighting, edited by W. Elenbaas, Philips Technical Library 1959, p. 104.

verter equipped with silicon controlled rectifiers, on the other hand, which is also capable of producing alternating current at frequencies up to 10 kc/s, can operate on a DC input of the order of 100 V and deliver a power in the region of 1 to 10 kW. This converter is therefore eminently suited for powering fluorescent lighting systems in trains and ships.

The latter type of converter can also be useful for operating fluorescent lamps in office buildings and factories which have been specially wired for the purpose: the converters are then operated from the ordinary electricity mains via rectifiers. The energy saving due to the lower losses in the ballasts and the higher luminous efficiency more than offset the losses in the rectifiers and converters. Once the prices of silicon controlled rectifiers have dropped, the net saving in itself will justify the investment in an installation of this kind, which at present is still rather high. Plans for a test installation at Eindhoven are now being worked out.

Converters using silicon controlled rectifiers

We shall confine ourselves in this article to a concise description of a converter developed in the electrical laboratory of Philips' Lighting Division, primarily for train lighting. First of all we shall deal briefly with the properties of the silicon controlled rectifier [9]) [3]).

The silicon controlled rectifier

The silicon controlled rectifier consists of four alternate layers of P-type and N-type silicon (*fig. 1*). There are two principal electrodes: the anode a and the cathode b, and one control electrode c. Provided the voltage between a and b does not exceed a specific value, the rectifier in the quiescent state passes no current (apart from a leakage current of no more than a few milliamperes); this holds for both polarities of the voltage between a and b. To make the rectifier conductive — which, without causing damage, is possible only in the forward direction (a positive with respect to b) — a momentary current injection in the control electrode is sufficient. A very high current is permissible in the forward direction (up to several tens of amperes, depending on the type [4])). The voltage drop is only 1 to 1.5 V, i.e. an order of magnitude smaller than in gas discharge tubes such as thyratrons and ignitrons. The non-conductive state returns only when the main current has dropped below a certain lower limit, called the holding current, below which insufficient charge carriers are generated in the P-N junctions. For certain types of silicon controlled rectifiers a peak voltage of 400 V (500 V for short periods) of both polarities is permissible in the non-conductive state, but in the forward direction not before the concentration of residual charge carriers after the passage of current has dropped to a level such that the leakage current is lower than the minimum value of the control current. Nor must the voltage in the forward direction rise so rapidly as to cause the resultant capacitive current in the P-N junctions to exceed the minimum value of the control current. The limiting value of the various quantities is dependent on the temperature inside the rectifier and on the nature and dimensioning of the circuit. Breakdown in the reverse direction causes irreversible damage.

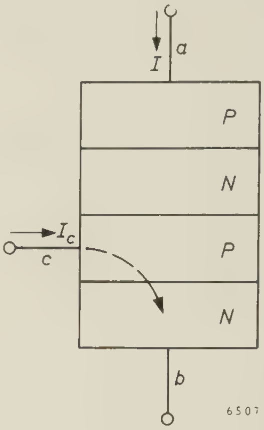


Fig. 1. A silicon controlled rectifier consists of four layers of silicon, alternately P type and N type. a anode, b cathode, c control electrode.

Fig. 2 shows a family of characteristics of a silicon controlled rectifier. It can be seen that the "breakdown voltage in the forward direction" decreases in value as the control current I_c increases.

As a commutating device the silicon controlled rectifier can often advantageously replace triodes,

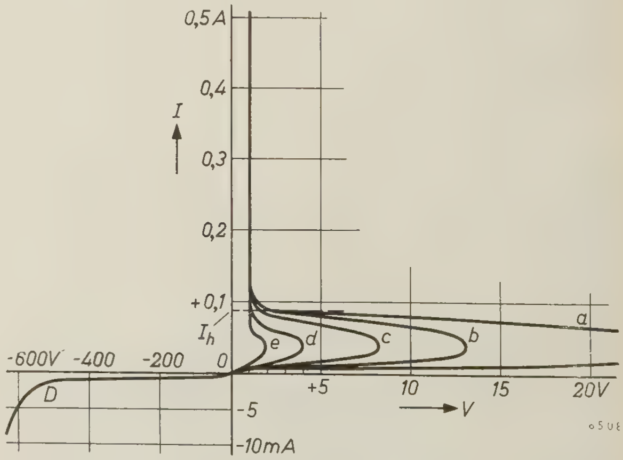


Fig. 2. Current-voltage characteristics of a silicon controlled rectifier. Top right: forward direction; bottom left: reverse direction (I and V are on different scales in the two different quadrants). The parameter is the control current I_c (= 0 in curve a, successively higher in curves b, c, d and e). I_h holding current. At D the rectifier breaks down, i.e. passes current in the reverse direction.

9) J. L. Moll, M. Tanenbaum, J. M. Goldey and N. Holonyak, P-N-P-N transistor switches, Proc. Inst. Radio Engrs **44**, 1174-1182, 1956.

thyratrons, ignitrons and transistors. In common with ignitrons and transistors this rectifier has no cathode that needs a certain time to heat up and that must be kept up to temperature. As mentioned, the voltage drop is lower than in thyratrons and ignitrons, and hence much lower than in triodes.

A drawback of converters using the new rectifiers, as opposed to mechanical converters, is their greater sensitivity to overloads. Overloading can easily cause permanent damage to the rectifying elements. To meet this difficulty the design should allow for a wide safety margin, and/or the converter should be provided with overload protection, preferably electronic.

A converter using silicon controlled rectifiers for train lighting

In order to bring silicon controlled rectifiers in a generator circuit recurrently from the non-conductive into the conductive state, periodic control pulses are needed. These are no problem to generate. A matter of more difficulty is the method of returning the rectifiers periodically to the non-conductive state at the high switching frequency which, for fluorescent lighting, is so advantageous.

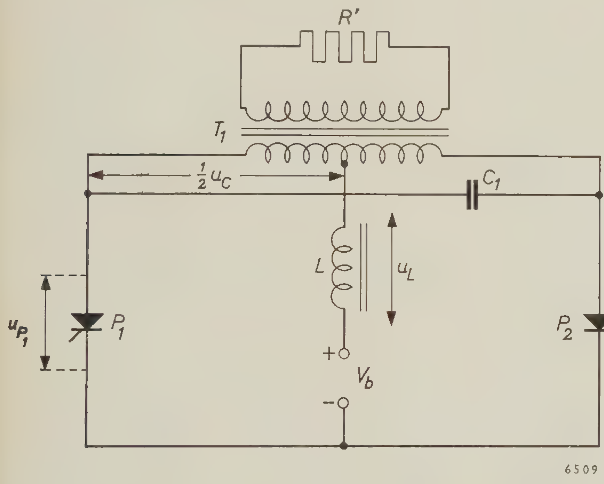


Fig. 3. Simplified circuit diagram (control circuit omitted) of a converter using silicon controlled rectifiers (P_1, P_2) in push-pull arrangement. T_1 transformer. C_1 commutating capacitor. L choke. V_b battery voltage. R' load resistance.

The simplest and most reliable method consists in using a series resonance circuit. The current then tends to have an oscillating character, but after the first half-cycle the rectifying element automatically becomes non-conductive.

Fig. 3 shows a simplified circuit diagram of a converter with silicon controlled rectifiers for train lighting. The two rectifying elements P_1 and P_2 are in a push-pull arrangement. The capacitor C_1 shunted across the primary of the transformer T_1 is called the commutating capacitor. The load on the transformer secondary is drawn here as a resistance R'. The situation when the first control pulse makes P_1 conductive can be represented by the equivalent circuit of *fig. 4*. Here R and C are the transformed values of R' and C_1 in fig. 3 in respect of one half of the transformer primary. The above-mentioned series resonant circuit is formed by C and the choke

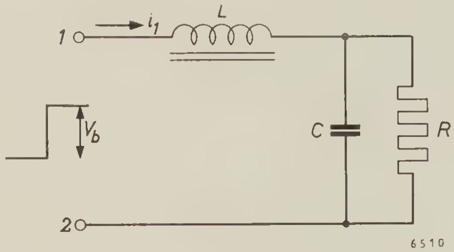


Fig. 4. Equivalent circuit for the moment at which the rectifying element P_1 in fig. 3 is made conductive. The DC voltage V_b then appears suddenly across terminals *1* and *2*. C and R are the transformed values of C_1 and R' in fig. 3 with respect to one half of the transformer primary.

L. When P_1 becomes conductive, the battery voltage V_b suddenly appears across terminals *1* and *2*. If the circuit is properly dimensioned, the current i_1 which now starts flowing will tend to have the waveform represented in *fig. 5*, i.e. a damped oscillation superposed on an exponentially rising current. However, at the moment $t = t_1$, at which i_1 drops to zero, the rectifying element becomes non-conductive so that i_1 remains for a while at zero. If we now apply the next control pulse to P_2 — some time *after* t_1 to give the charge carriers in P_1 an opportunity to recombine sufficiently — the process will be repeated, except that some quantities change

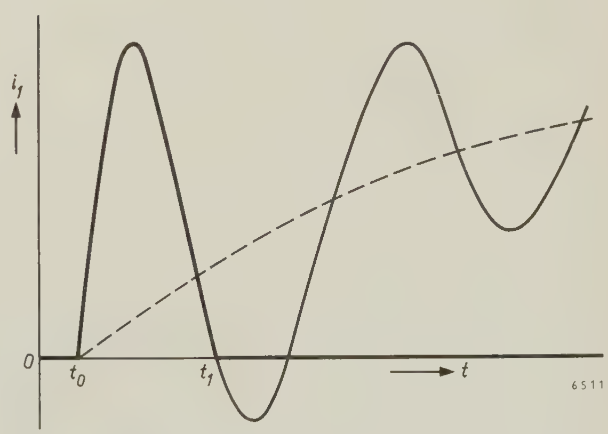


Fig. 5. The full line shows the variation of the current i_1 in the circuit of fig. 4: damped oscillation superposed on a current variation approximately of the form $V_b(1-e^{-at})/R$ (dashed line). Since the rectifying element prevents the current from changing direction, in the circuit of fig. 3 the current i_1 remains zero from point t_1 onwards, so that only the thickly drawn portion of the waveform is obtained.

their sign and that, since C retains a certain charge, the initial conditions are different. The current i_2, which now starts to flow through P_2, will also remain at zero after the first half cycle. A moment later, P_1 is again made conductive, and so on. Periodic repetition of the control pulses produces a certain steady state, resulting in an alternating voltage across the transformer (fig. 3).

Brief analysis

The voltages in fig. 3 satisfy the following equation:

$$u_{P_1} = V_b + u_L + \tfrac{1}{2}u_C \,. \qquad (1)$$

We distinguish two states of the circuit: 1) one of the two rectifying elements is conductive and the other not, and 2) neither is conductive.

1) *One rectifying element (P_1) is conductive and the other not*
As an approximation, then, $u_{P_1} = 0$, so that from (1):

$$\tfrac{1}{2}u_C = -(V_b + u_L) \,. \qquad (2)$$

The current i_1, which flows from t_0 to t_1 through P_1, can be shown to have the value:

$$i_1 = \frac{V_b}{R} - \frac{V_b}{R \sin\varphi} e^{-\alpha t} \sin(\omega t + \varphi) + \frac{V_b + \tfrac{1}{2}U_C}{\omega L} e^{-\alpha t} \sin \omega t \,, \qquad (3)$$

where $\alpha = \dfrac{1}{2CR}$,

$$\omega = \sqrt{\frac{1}{LC} - \alpha^2} \,,$$

$$\varphi = \tan^{-1}\frac{\omega}{\alpha} \,,$$

U_C = voltage across C at the time $t = t_0$. (U_C can be found from a further calculation, not given here.)

For the voltage u_L during the interval t_0-t_1 we find:

$$u_L = -\frac{V_b}{\omega CR} e^{-\alpha t} \sin \omega t + \frac{V_b + \tfrac{1}{2}U_C}{\sin\varphi} e^{-\alpha t} \sin(\omega t - \varphi) \,. \qquad (4)$$

The waveforms of i_1 and u_L during the interval t_0-t_1 are roughly illustrated in *fig. 6a* and *b*. Assuming that U_C is known, the waveforms of u_C and u_{P_1} can be constructed with the aid of (1) and (2) (see fig. 6*c* and *d*).

2) *Both rectifying elements are non-conductive.* After the moment t_1 no current passes through P_1. Up to the moment t_2 at which P_2 receives a control pulse, the R-C circuit is left to itself, so that C discharges exponentially with the time constant RC. Since i_1 and i_2 are now zero, so too is u_L, and the waveforms of the various voltages during the interval t_1-t_2 are easily found; see fig. 6*b*, *c* and *d*. The variation from the moment t_2 can also be found without much difficulty. For a more detailed analysis, reference may be made to the literature [10]).

It can be seen from fig. 6*d* that the peak voltage across the rectifying elements can considerably exceed V_b, the precise value depending on the dimensioning of the circuit and the load. This should be taken into account when choosing the value of V_b and the type of rectifying element.

It follows from (3) that the choice of L and C determines the duration t_0-t_1 of the conduction in every half cycle T. It is therefore possible after every pulse to give the rectifying elements a certain "recovery time", from t_1 to t_2 ($t_2 = t_0 + \tfrac{1}{2}T$) as needed to ensure proper operation.

The complete circuit diagram of the converter is shown in *fig. 7*. The resistive load of fig. 3 is now replaced by a number of "TL" S lamps (chosen because they operate without a starter). Half the

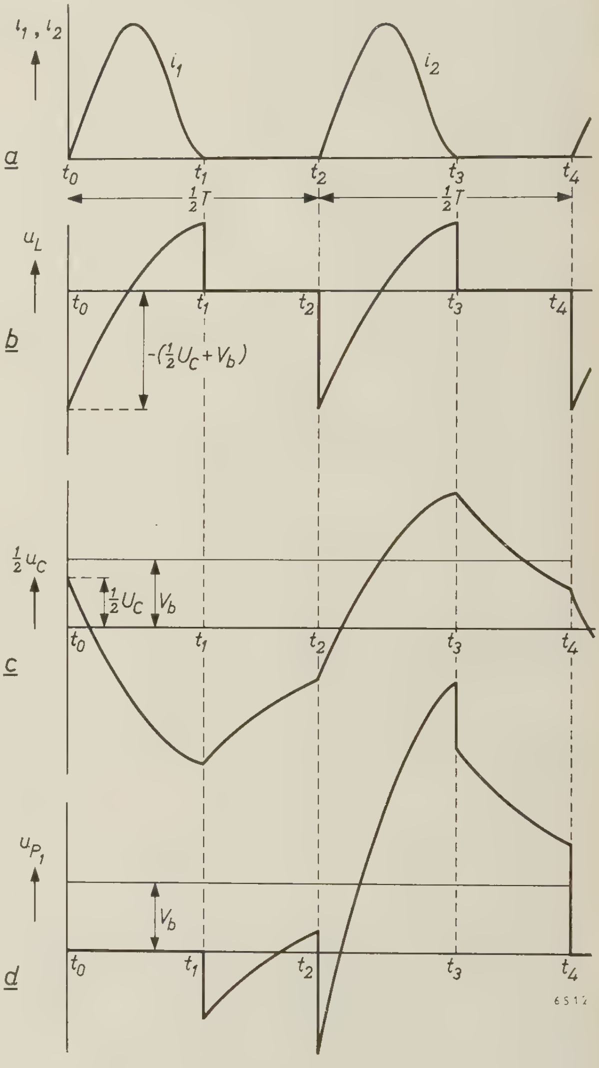


Fig. 6. Currents and voltages in the circuit of fig. 3. At the moments t_0 and t_4 the rectifying element P_1 receives a control pulse; at the moment t_2 a control pulse is received by P_2, and at t_1 and t_3 the currents i_1 and i_2 respectively are zero. t_0 and t_4 are separated by one period T.
a) Current i_1 through P_1 and current i_2 through P_2.
b) Voltage u_L across choke L (from t_0 to t_1 given by (4), from t_1 to t_2 equal to zero).
c) Voltage $\tfrac{1}{2}u_C$ over one half of the transformer primary (from t_0 to t_1 given by (2) and (4), from t_1 to t_2 varying as $-\exp(-t/RC)$).
d) Voltage u_{P_1} across P_1:
t_0 - t_1 . . . . $u_{P_1} \approx 0$,
t_1 - t_2 . . . . $u_{P_1} = V_b + \tfrac{1}{2}u_C$,
t_2 - t_3 . . . . $u_{P_1} = u_C$,
t_3 - t_4 . . . . $u_{P_1} = V_b + \tfrac{1}{2}u_C$.

[10]) W. Schilling, Berechnung des Parallelwechselrichters bei ohmscher Belastung, Arch. Elektrotechn. **29**, 119-130, 1935. C. F. Wagner, Parallel inverter with inductive load, Trans. Amer. Inst. Electr. Engrs **55**, 970-980, 1936.

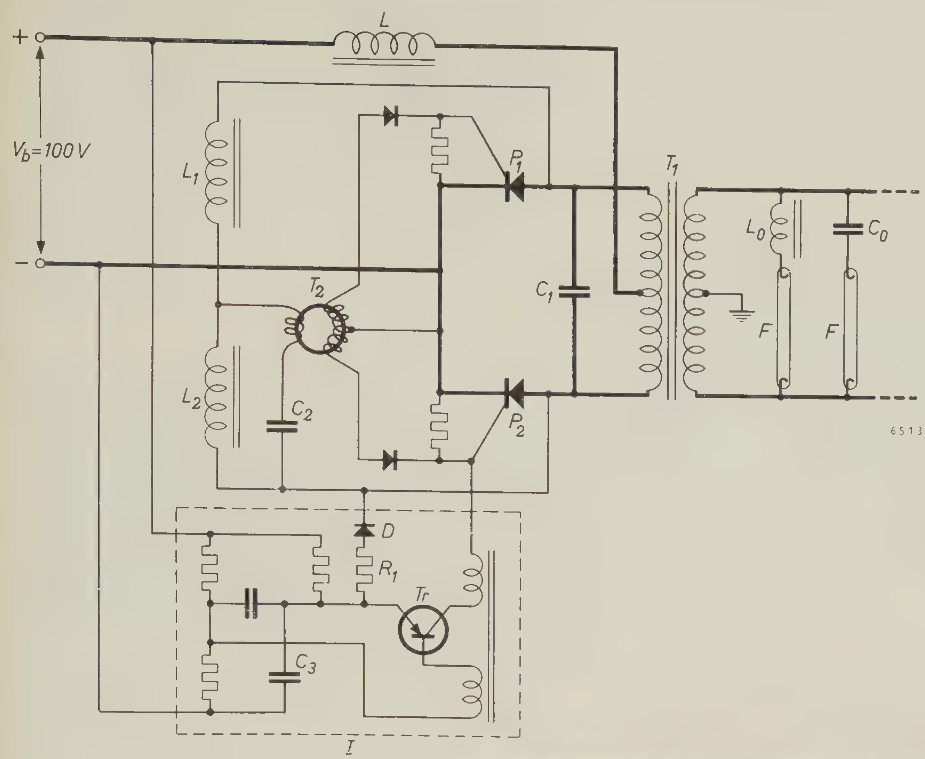


Fig. 7. Basic circuit of a converter using silicon controlled rectifiers, designed for train lighting. P_1, P_2, L, C_1, T_1 and V_b (here 100 V) as in fig. 3. F fluorescent lamps of type "TL" S (one half in series with chokes L_0, the other half in series with capacitors C_0). T_2 pulse transformer with ferrite core (rectangular hysteresis loop) fed by the converter itself via network L_1-L_2-C_2.

I starting-pulse generator. Capacitor C_3 discharges periodically through transistor Tr and the control electrode and cathode of P_2. Once the converter is oscillating, the anode of P_2 becomes negative with respect to the cathode during a part of each cycle (see fig. 6*d*); this negative voltage discharges capacitor C_3 through diode D and resistor R_1, which makes the starting-pulse generator inoperative.

number of lamps have a choke as ballast with an inductance L_0, the other half a small capacitor of capacitance C_0. The value L_0C_0 is chosen near to resonance at the frequency of the converter. Since the voltage is roughly sinusoidal (see fig. 6*c*), this load is not much different from a resistive load for the converter.

When the converter is switched on, it is set in operation by starting pulses from the transistorized pulse generator *I*. As soon as the converter starts oscillating, the pulse generator is automatically made inoperative (see caption to fig. 7). The control pulses are now delivered by the pulse transformer T_2, which has a ring-shaped ferrite core with a rectangular hysteresis loop. The primary of T_2 is fed from the converter itself via chokes L_1 and L_2 and the capacitor C_2. The pulse repetition frequency can be adjusted by varying L_2 and C_2.

Fig. 8 shows an experimental 1 kW converter designed on this principle, for operation from a 100 V DC supply. The load consists of 24 "TL" S 40 W lamps. *Fig. 9* shows a later version of this converter, intended for an experimental lighting installation in a train of the Netherlands Railways. Fig. 9

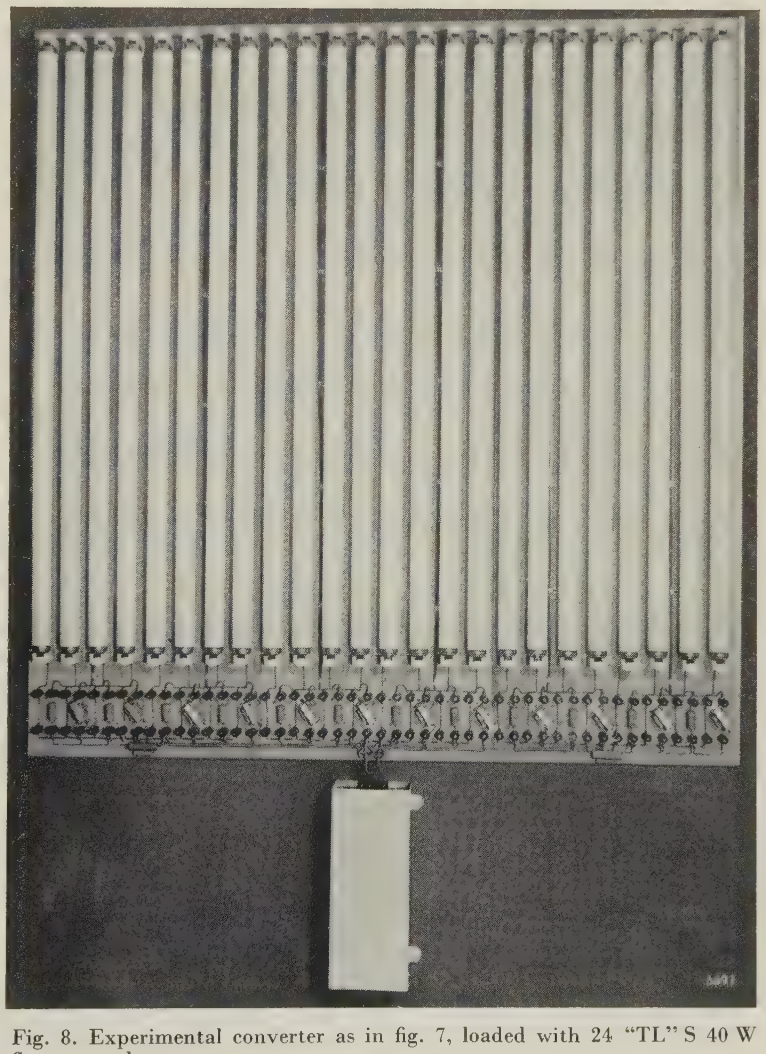


Fig. 8. Experimental converter as in fig. 7, loaded with 24 "TL" S 40 W fluorescent lamps.

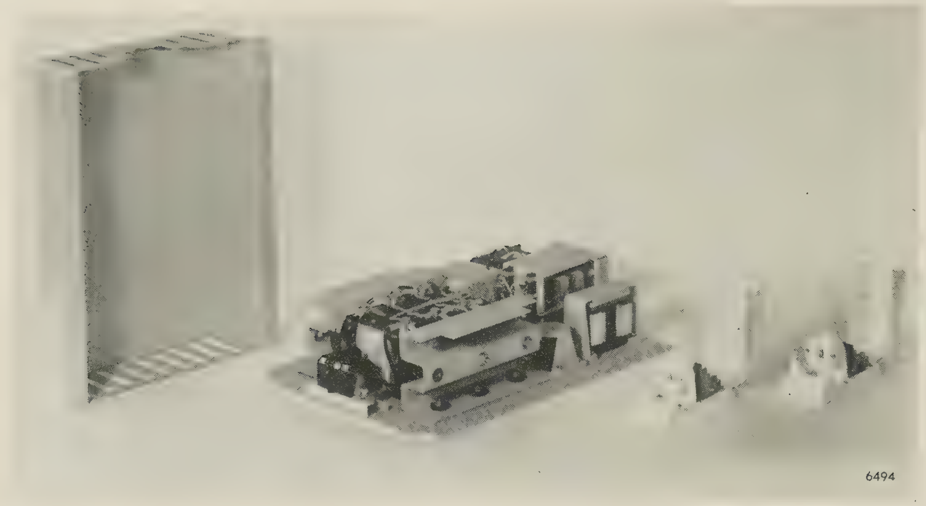


Fig. 9. Converter on the principle of fig. 7, designed for a fluorescent lighting system on trial in a train of the Netherlands Railways. Input voltage 100 V, power 1 kW, frequency 7 kc/s, efficiency better than 85%, weight approx. 10 kg. On the right, two standard lamp holders for a "TL" lamp, each fitted with a "ballast" (in one a choke, in the other a capacitor).

also gives an idea of how small the "ballasts" are, so small indeed that they can be accommodated in the standard covers of the lamp holders.

The frequency of the converter in fig. 9 is 7 kc/s, the efficiency more than 85%, and the weight about 10 kg.

Summary. For operating fluorescent lamps from a DC source (as in trains) use has mainly been made hitherto of rotary DC/AC converters. Electronic converters are now gaining ground, and a new type is discussed here which is equipped with *P-N-P-N* silicon controlled rectifiers. These rectifiers can handle a considerably higher power than transistors and have a voltage drop of only 1 to 1.5 V, which is an order of magnitude smaller than in thyratrons and ignitrons. Converters with silicon controlled rectifiers have a much wider field of application than rotary converters, which they will largely supersede in the near future. They can operate in the frequency range from 5 to 10 kc/s. This has particular advantages for fluorescent lighting, enabling small, light-weight ballasts to be used which have extremely low losses, and giving a luminous efficiency about 10% higher than at 50 c/s. A description is given of a converter using silicon controlled rectifiers which has been designed for train lighting; the input voltage is 100 V, the power 1 kW, the frequency 7 kc/s. In conjunction with mains rectifiers the new converters will be useful for fluorescent lighting in offices and factories. It is expected that the present fairly high costs of such installations will be reduced in the not too distant future, to such an extent that the energy savings will make them a profitable proposition.

AN INSTRUMENT FOR AUTOMATICALLY RECORDING ISOCANDELA DIAGRAMS OF BEAMED LIGHT SOURCES

by W. BÄHLER *).

535.247.4:628.971.85:629.113

One of the problems facing the designer of beamed light sources is to produce a beam pattern that meets specific requirements. For lighting airfields, for example, beams are required that are fairly broad in the horizontal plane but very narrow in the vertical. For beacon lights, signalling lamps and car headlamps the requirements are complicated, and where beacons are concerned they differ from case to case. For flood-lighting, too, beams are often needed that are not simply radially symmetrical.

As an example we shall briefly discuss, with reference to *fig. 1*, the present specifications applicable in many European countries to the dipped beam or passing light of car headlamps [1]). Broadly speaking, the beam should be such that a motorist driving on an unlighted road retains sufficient lighting to be able to see the road ahead without dazzling oncoming traffic. Fig. 1 gives a perspective drawing of a road 6 m wide as "seen" by a car headlamp at a height of 75 cm above the road surface, in the middle of the right half of the road. If we draw the system of lines in this figure, with the given dimensions, on a screen and set it up 25 m away from a headlamp, the light thrown by the headlamp on to the screen should meet the follow-

*) Philips Research Laboratories Eindhoven.

[1]) A comparison of the properties of the (then) European and American dipped beam has been given by J. B. de Boer and D. Vermeulen, Philips tech. Rev. **12**, 305, 1950/51.

ing requirements. In the first place the transition from light to dark (the cut-off) should be sharp enough for it to be used to adjust the headlamp. This is done in such a way that the cut-off falls on the left half of the screen on a horizontal line 25 cm below the line *h-h*; on the road this appears as a transverse line at a distance of 75 m in front of the car. Right of centre the light-dark cut-off should run upwards. When the lamp is thus adjusted, the illumination in the various zones and points of the screen should not exceed the values indicated in red. As can be seen, the lower boundary of zone III on the right side is inclined at 15° to the horizontal. The illumination of the right kerb must also be fairly high. A beam meeting these requirements will thus clearly be asymmetric [2]).

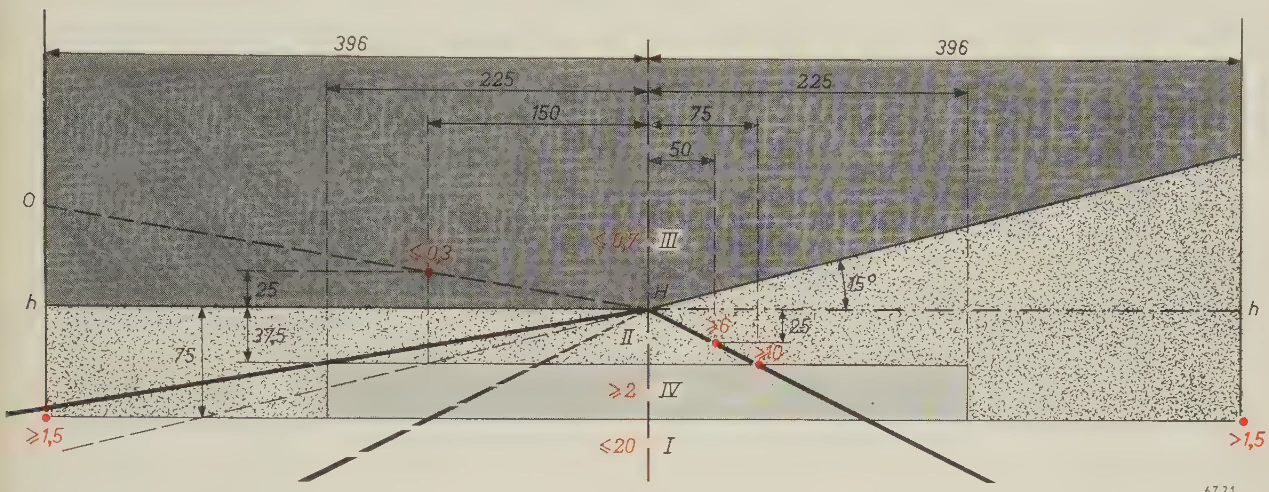


Fig. 1. Perspective sketch of a 6 metre wide road as seen by an eye 75 cm above the middle of the right lane. The dashed line *HO* is the line roughly followed by the eye of an oncoming motorist. To ascertain whether the passing light of a car headlamp complies with the requirements, this diagram, with the dimensions given, is drawn on a screen which is placed at a distance of 25 m from the lamp. The illumination at various points and in zones *I-IV* of the screen is required in most European countries to meet the standards indicated in red. The headlamp should be aligned so that the sharp light-to-dark cut-off required on the left lane coincides on the screen with a line 25 cm below the line *h-h* (that is 75 m ahead of the car on the road). After switching to the driving light the illumination at point *H* should not be less than 90% of the maximum.

It will be evident that the designer of a beamed light source which must comply with these complicated requirements will want to measure the level of illumination at numerous points of the beam projected by the headlamp on to the screen. The usual practice is to determine a series of points where the illumination has a specific value and to draw through these points a closed curve, called an isolux curve. Since the headlamp produces the same luminous intensity in all directions corresponding to the points in such a curve (at least in the case of narrow beams) the curve may equally be regarded as an isocandela curve. A complete light-distribution diagram consists of ten or more isocandela curves.

In some cases the demands made on the accuracy of the isocandela curves are so high as to call for an exceptionally large number of measuring points. To eliminate the time-consuming measurements which this involves, an instrument has been designed at Eindhoven which is capable of tracing isocandela curves automatically. All that has to be done is to adjust on the instrument the luminous intensity for which an isocandela curve is required. In this way a complete isocandela diagram can be recorded in about 20 minutes.

In this article we shall describe the operation and design of this isocandela-diagram recorder [3]). We shall begin with the principle of its operation, and it will be shown that the instrument can be regarded as a closed control loop. After discussing the most important properties of the recorder, we shall describe its construction. In the last part of the article, we shall discuss the various parts of the recorder from the point of view of control theory.

Principle of operation

The principle underlying the operation of the isocandela-diagram recorder can be explained by considering the luminous intensity pattern as a

[2]) See e.g. J. B. de Boer, The "Duplo" car headlamp bulb with an asymmetric dipped beam, Philips tech. Rev. **16**, 351-352, 1954/55.

[3]) A brief description of a provisional model of the instrument was given in Philips tech. Rev. **20**, 288, 1958/59.

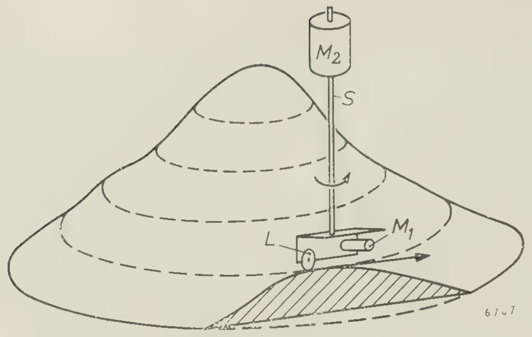


Fig. 2. Principle underlying the operation of the isocandela-diagram recorder, illustrated by considering an instrument that automatically draws contour lines on a mountain. The wheel L of the trolley is driven by a motor M_1. The trolley is fitted with an altimeter. If the altitude at which the wheel runs over the mountain slope differs from the preset value, the difference signal delivered by the altimeter actuates the steering motor M_2, producing a change of course that returns the trolley to the required contour.

mountain landscape (*fig. 2*). The height corresponds to the level of illumination on the screen, and the isolux lines are contour lines in the mountain landscape. The instrument which measures the illumination, the photocell, is in this case an altimeter. The latter is mounted on a single-wheeled trolley which is driven around the contours by a small motor. The trolley is fixed to the lower end of a vertical shaft, the steering rod, the position of which is controlled by a servo-motor.

From fig. 2 it can be seen that, if the steering rod is not turned, the trolley will not go on following the contour line on which it started. In the case sketched here it will run off the mountain, and the height indicated by the altimeter will be lower than that of the wanted contour line. The fact that any deviation from the desired value is immediately ascertained creates the possibility of making the servo-motor do its work correctly. For that purpose the deviation is converted into an electric signal, which is applied after amplification to the servo-motor. If the components are coupled with the right polarity, the servo-motor will now turn the steering rod in such a way as to correct the deviation from the proper course (in our case the contour line).

It may be concluded from the foregoing that the steepness of the slope along which the trolley moves must influence the behaviour of the instrument. On an almost *flat* part of the slope a given deviation from the correct course will produce only a slight change in the altimeter reading; in other words, the signal used to control the trolley will be small compared with that for a deviation of the same magnitude on a *steep* part of the slope. We mention this fact at the present stage because of its important bearing on the stability of the control loop.

The operation of the isocandela-diagram recorder itself is represented schematically in *fig. 3*. The difference compared with the contour recorder just described is that instead of the light-distribution pattern ("mountain") remaining stationary and the photocell (the "trolley") moving along the

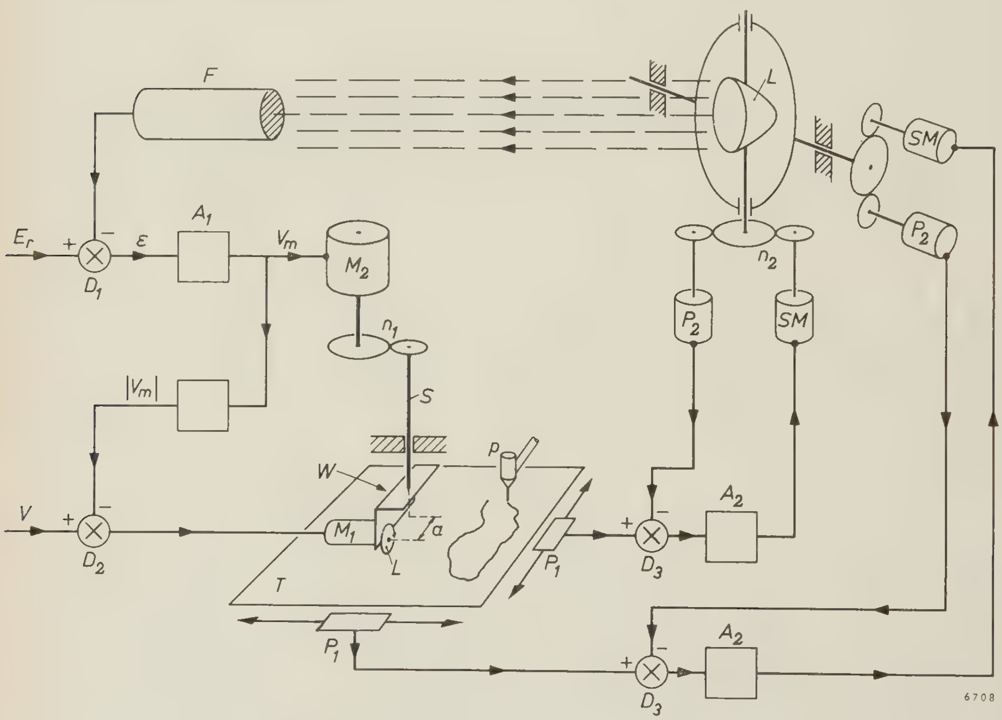


Fig. 3. Basic diagram of the isocandela-diagram recorder. Top right the lamp L, whose azimuth and elevation can be varied within defined limits. F calibrated photocell in fixed position. The output signal from F is compared in D_1 with the variable reference signal E_r. The difference signal ε is amplified in A_1 and energizes the steering motor M_2, which, via a reduction gear, steers the trolley W by turning the steering rod S, mounted in fixed bearings. The drive wheel L of the trolley is driven by motor M_1. T recording table which can be moved in its plane, by L, in two mutually perpendicular directions. The positional coordinates of T are each converted by separate servo-systems into azimuth and elevation of the lamp. Each servo-system consists of a position pick-off P_1 by the table, a servo-motor SM, a position pick-off P_2 by the lamp, a difference circuit D_3 and an amplifier A_2. The isocandela curve corresponding to the value of E_r is traced by a fixed stylus p on a sheet of paper fixed to the table T. The motor M_1 is supplied with the signal delivered by D_2, being the difference between the absolute value $|V_m|$ of the control-motor voltage and a constant voltage V. The point of contact of the wheel on the table is not in line with the steering rod but at a small off-set a from the axis of the rod.

screen, the photocell remains stationary and the beamed light source is rotated. Middle left we again see the trolley at the lower end of the steering rod S, which here turns in fixed bearings. The wheel of the trolley is driven by the motor M_1. In its turn the wheel sets in motion the recording table T, which can move in its plane in two mutually perpendicular directions. The two coordinates that determine the position of the recording table are each converted by a positional servo system into an angle of rotation, namely the azimuth and the elevation of the lamp L. The illumination produced by the lamp in this position on the stationary photocell F is converted by the latter into an electrical signal. This is compared in the circuit D_1 with a reference signal E_r, which corresponds to the value of illumination for which a curve is required. The difference signal ε is amplified in A_1 and fed to the steering motor M_2. A fixed stylus maps out the curve on graph paper fixed on the recording table. In principle it is immaterial where the paper and stylus are situated; the positional coordinates of each point on the recording table always vary in the same way, and the curve traced is therefore in any case congruent with the path described by the wheel.

The diagram produced by the instrument is not an exact scaled-down copy of the diagram that might be drawn on the screen referred to (fig. 1). The difference is that the coordinates used are the azimuth and elevation of the given direction — i.e. the angles — and not the distance on the screen. As will be known, this makes no difference where small angles are concerned.

It can be seen that the essence of the method is the feedback brought about between photocell and lamp by D_1, the steering motor and trolley, the recording table and the positional servo systems, and which automatically ensures that the lamp points only in those directions where the illumination has the desired value.

As can be seen from the figure, the driving motor M_1 is not fed with a constant voltage but with the difference between the absolute value of the input signal of the steering motor M_2 and a constant voltage V. The significance of this will be discussed presently, as also will the fact that the point where the wheel touches the recording table T does not lie in line with the steering rod but at a distance a to one side.

The instrument as a control loop

Consideration of fig. 3 shows, as mentioned in the introduction, that the system can be regarded as a closed control loop. *Fig. 4* gives a schematic diagram of this loop.

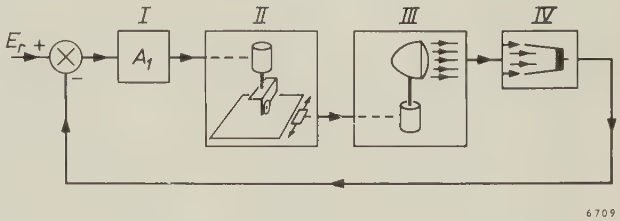


Fig. 4. The isocandela diagram recorder as a control loop. Block *I* represents the amplifier A_1 of fig. 3, block *II* the control motor with trolley, table and position pick-offs, block *III* the rest of the positional servo-systems and the lamp, and block *IV* the photocell whose output signal is compared with the reference signal E_r.

Although the characteristics of the components of the control loop will be dealt with at length at the end of this article, it will be useful here to discuss briefly the characteristics of the loop as a whole. In doing so we shall make use of a simplified formula for the transfer function $KG(j\omega)$ of the open loop — i.e. the complex ratio between the output signal of the photocell and the input signal of A_1 (fig. 4) for the case where the feedback is interrupted — and derive from this formula the Bode and Nyquist diagrams [4]). The formula reads:

$$KG(j\omega) \approx$$
$$\approx \text{const.} K_E R_p(E) \frac{1 + j\omega\tau_3}{(j\omega\tau_0)^2(1 + 2\zeta j\omega\tau_6 - \omega^2\tau_6{}^2)}, \quad (1)$$

where $\tau_3 = a/v$ is the quotient of the above-mentioned distance a (see fig. 3) and the velocity v of the trolley, i.e. τ_3 is the time taken by the wheel to cover the distance a. Further, τ_0 is the unit of time, τ_6 a time constant whose value is determined by the properties of the positional servo-systems, K_E the gradient of the illumination at the place which the photocell "sees" at the relevant moment — a quantity which varies during the tracing of the curve — and ζ is a damping constant connected with τ_6 and with various constants of the system which do not otherwise appear in (1) (see final section). Finally, the factor $R_p(E)$ is due to the photocell, its value varying with the illumination E.

The pertaining Bode diagram, approximated by three straight lines, is sketched in *fig. 5*, and the Nyquist diagram in *fig. 6*. The successive straight lines have the slopes —2, —1 and —3. The point of

[4]) For the concepts, definitions and methods of calculation in control engineering, as used in this article, the reader may be referred to three articles on control-engineering subjects, which appeared a few months ago in this journal (pages 109, 151 and 167 of numbers 4, 5 and 6 respectively).

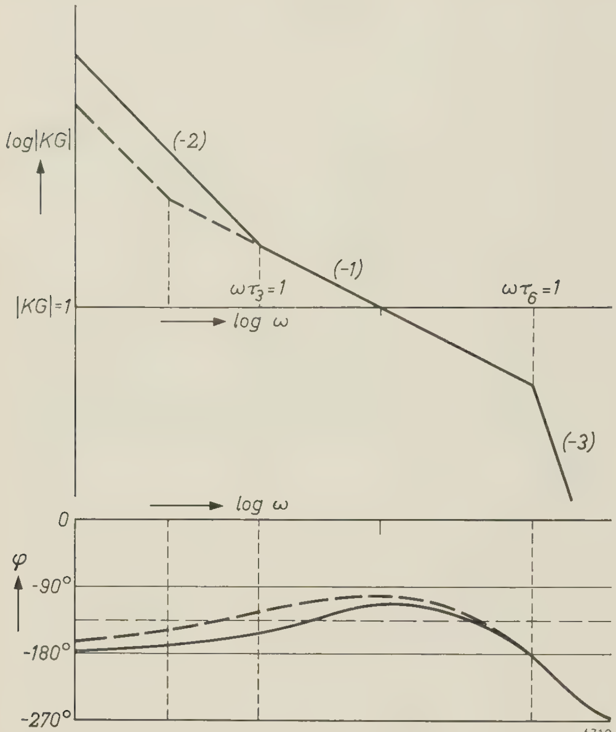


Fig. 5. Bode diagram (schematic) of the complete open loop. The amplitude characteristic, approximated by straight lines, consists of three branches of slope —2, —1 and —3. The frequency $\omega = 1/\tau_3$ at which the first break occurs varies with the peripheral velocity v of the wheel and the distance a (cf. fig. 3): $\tau_3 = a/v$. The phase shift φ at this frequency is more than 135°. The dashed lines show how the two characteristics change as v decreases. The gain then becomes lower and the phase margin (i.e. 180° — $|\varphi|$) wider.

intersection of the first two lines lies on the vertical $\omega = 1/\tau_3$. The phase shift at this frequency is more than 135°. The second break occurs at $\omega = 1/\tau_6$. The phase shift here is about —180°. (The phase shift at $\omega = 1/\tau_3$ is closer to —135° the greater is the difference between τ_3 and τ_6 and the smaller is ζ.)

The Nyquist diagram shows that the system is stable when the various constants have the values corresponding to the curves in figures 5 and 6. Going along the Nyquist curve from the point

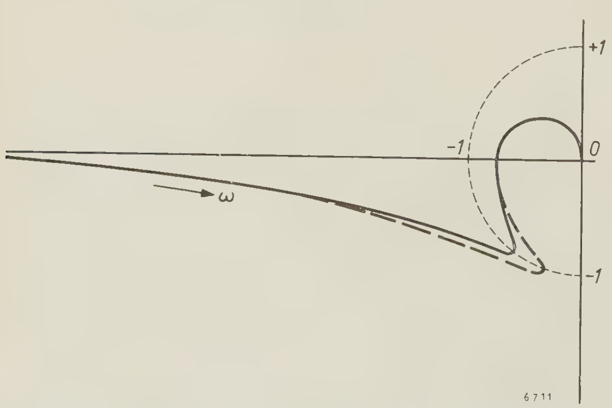


Fig. 6. Nyquist diagram derived from fig. 5. Here too, the dashed line relates to a lower value of v than the full line.

corresponding to $\omega = \infty$ (the origin) to the point corresponding to $\omega = 0$, we see that the point (—1, 0) is everywhere on our right — except where it is screened by another part of the curve [5]).

The stability characteristics differ, however, from those encountered in simple control systems. Here, too, of course, instability occurs if the gain is increased — the point (—1, 0) in fig. 6 then shifts to the right in relation to the curve — but there is also a lower limit to the gain. Although there is no instability when the gain is very small, the phase shift in such a case is so close to —180° — i.e. the phase margin is so small — that the damping of the system is too weak and oscillations last too long.

As indicated above, K in this control loop is not a constant that can be fixed at a desired value: K is proportional to the gradient K_E of the illumination pattern. These variations may be so considerable — as much as a factor of 20, see *fig. 7* — as to jeopardize the stability of the system. The inconstancy of R_p presents no difficulties. Along one and the same isolux contour E is of course constant and so too then is R_p. The change in R_p upon

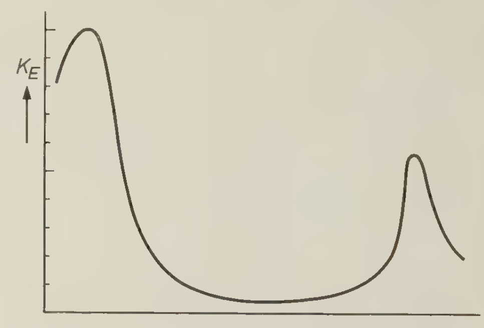


Fig. 7. Variation of the gradient K_E of the illumination along the isocandela curve for 4.0 lux in diagram A on p. 243 of this number. The extreme values of K_E are no less than a factor of 20 apart.

the transition to a succeeding value of E can be easily compensated by resetting the loop gain at the old value before tracing a further isolux curve.

To explain the method of solving the difficulty presented by the variation of K_E, we shall first discuss the manner in which $G(j\omega)$ changes when τ_3 is varied. We begin with the extreme case where the distance a is 0 and thus τ_3 is also zero. In this case the Bode diagram, as far as amplitude is concerned, consists solely of two straight lines of slope —2 and —4, and the absolute value $|\varphi|$ of the phase shift is $\geqq$ 180° for all frequencies (= 180° for the low frequencies and > 180° for the high).

5) The simplified version of Nyquist's stability criterion used here is equivalent to that used in the first article mentioned in reference [4]).

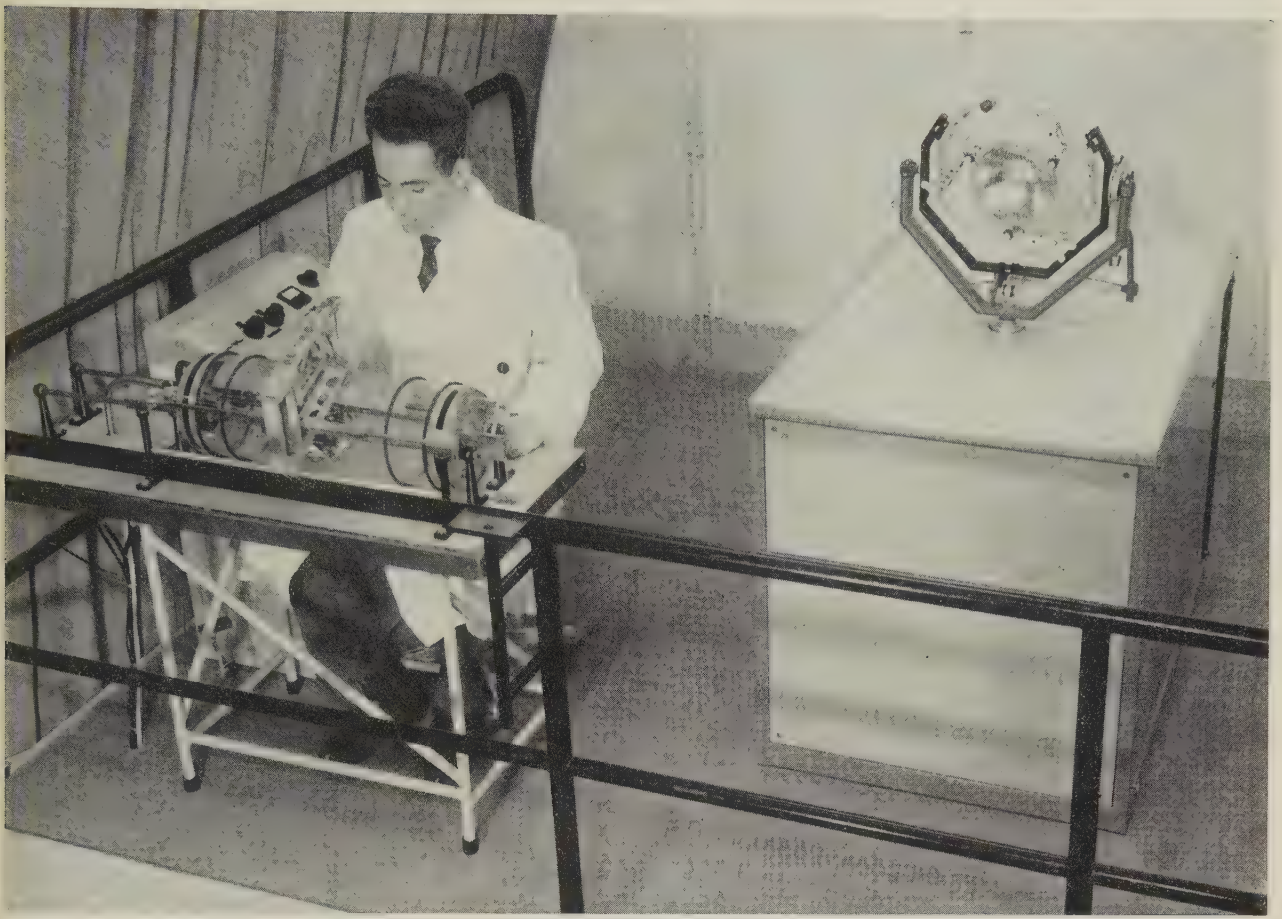


Fig. 8. View of the platform containing the major part of the equipment. The recording portion is mounted on the table, left (the recording table T of fig. 3 is here "rolled up" to form a drum). Behind the operator can be seen the control desk. The lamp holder, right, is mounted on a cabinet which provides a dust-free enclosure for the associated control mechanisms. The photocell is situated 25 metres from the lamp. Much of the electronic circuitry is contained in a rack under the platform.

For the low frequencies the Nyquist curve coincides with the negative real axis and is even above it for the high frequencies. At no value of amplification, then, can the system possibly be stable. *It is therefore an essential condition for the stability of the instrument that the distance "a" should not be equal to zero.*

The effect of limited variations of v on the Bode diagram is to move the first break along a line of slope —1. If τ_3 is increased the loop gain therefore decreases in the range of low frequencies. At the same time the phase margin widens (see dashed lines in fig. 5 and fig. 6). It is this effect that is used for more or less compensating the troublesome variation of K with K_E. Returning to fig. 3, we see that the motor M_1 that drives the wheel does not turn at a constant speed, but is controlled by the difference between the absolute value of the control signal, which is proportional to K_E, and a constant voltage V, which is higher. If K_E increases, then, the motor turns more slowly and τ_3 increases. The rise in K due to the increase of K_E is thus opposed by the associated increase in τ_3.

This rough compensation of the variations of K_E is sufficient for practical purposes, and is much simpler than a method involving measuring K_E and varying the gain factor of A_1 correspondingly. It should be noted in this connection that the velocity of the driving wheel varies not only with K_E but also with the radius of curvature of the isocandela curve. This is an additional advantage, since it means that sharp corners are carefully traced.

Particulars of construction

We shall now review the construction of the various components of the isocandela-diagram recorder [6]). It should be mentioned first of all that the mechanical operation of the instrument differs in one point from that implied in fig. 3. In that figure the steering rod and the stylus are represented for simplicity as being in fixed positions, and the recording table T as capable of moving in two direc-

[6]) The solution of the various problems of design was the work of L. de Wit of Philips Lighting Division.

tions at right angles to each other. The provisional version described earlier in this review [3]) already differed from this arrangement to the extent that the table moved in one direction and the trolley together with the stylus in the other. In the definitive version we have gone a step further and have turned the recording table into a drum which can rotate about its axis. During rotation the drum, like the earlier recording table, moves in its own plane in one coordinate direction. The paper is attached to the *outside* of the drum, and the driving wheel moves over the *inside*.

Fig. 8 shows the form and arrangement of the equipment. On the left can be seen the drum and the control desk, on the right the lamp-holder mounted on top of a cabinet which contains the positional servo-systems.

The drum with trolley and stylus

We shall now explain the construction of the drum and ancillary equipment with reference to *fig. 9*. On the table, at each end of the drum, are two supports *1*, which carry two parallel horizontal rods *2*. Attached to these rods are the two end plates *3* of the drum. Inside the drum itself the rods act as guide rails along which the carriage moves. The cylindrical surface of the drum, which is made of transparent plastic material, rotates about the two fixed end plates, which are provided with bearings in the form of steel end rings.

The trolley consists of two parts. The upper part (*D*), the "carriage", is equipped with three ball bushings for running on the guide rails. Also mounted on the carriage are the steering motor, the bearing for the steering rod and a reduction gear between the steering motor and the steering rod (see also *fig. 10*). The other part of the trolley (*W*) is at the bottom end of the steering rod and consists of a holder which carries the wheel and its driving motor.

By means of a lever system the wheel can be lifted from the drum surface, enabling drum and trolley to be moved independently of one another. The lever mechanism is operated by the handle *4*.

The stylus holder *5* can move parallel to the axis of the drum along the rod *6*. It is connected by cords to the trolley: if the trolley moves to the right, the stylus goes just as far to the left, and *vice versa*.

The paper on which the diagrams are drawn is fixed to the outside of the drum by rubber rings *7*.

The two positional coordinates, that is the angle of rotation of the drum and the position of the trolley on the rails, are transmitted electrically

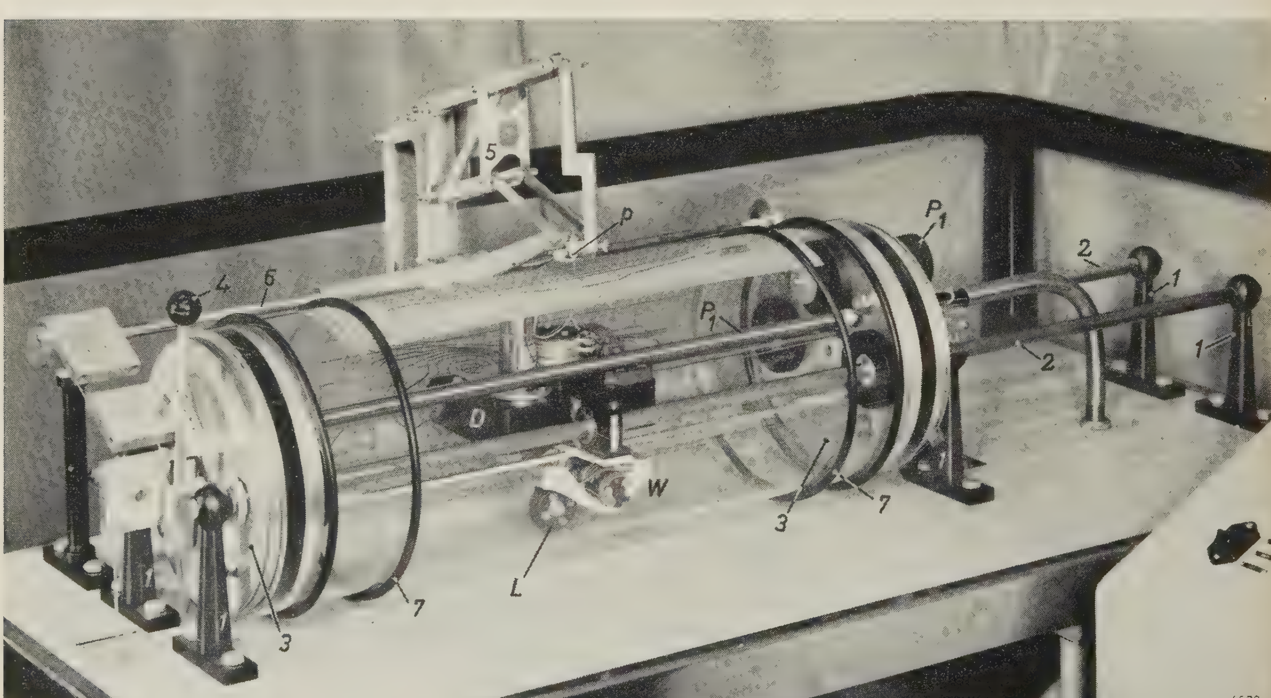


Fig. 9. The recording drum. *1* four supports for the horizontal rods *2* which act as guide rails inside the drum. *3* end plates fixed to *2*, also acting as drum bearings. *W* is the trolley connected to the bottom of the steering rod. *D* carriage, containing the steering-rod bearings and the steering motor. *4* handle for raising the trolley wheel *L* from the drum. *5* holder of stylus *p* on guide rail *6* and connected by cords to the trolley. *7* two rubber rings for clamping recording paper to the outer surface of the drum. P_1 positional potentiometers which follow the translational motion of the trolley and the rotation of the drum.

to the lamp, as mentioned in the introduction. For this purpose the drum is equipped with two potentiometers (P_1 in figs 9 and 10). One of them is a rotary potentiometer and is mounted on the outer face of one of the end plates. It is set in motion via a gear transmission by the steel ring at the relevant end of the drum, the ring being provided with teeth for this purpose. The other potentiometer is wound on a rod inside the drum and is secured, parallel with the guide rails, to the end plates. The pertaining slide contact is fixed to the trolley.

The construction of the recording part of the instrument described here is preferable for various reasons to a flat table. In the first place the dimensions of the apparatus are considerably reduced by "rolling up" the table. This is not only due to the drum form as such, but also to the fact that a flat surface would have to be appreciably larger than the "rolled out" drum, because the wheel, in order to avoid the risk of smudging, must not pass over a part of the paper that has already been traced. With the drum this is no problem because the paper and the wheel are on different sides of the wall. In the second place the drum construction makes it possible to accommodate part of the mechanism in a dust-free space. This is particularly important for the proper operation of the rod-potentiometer and for the guide rails along which the trolley moves.

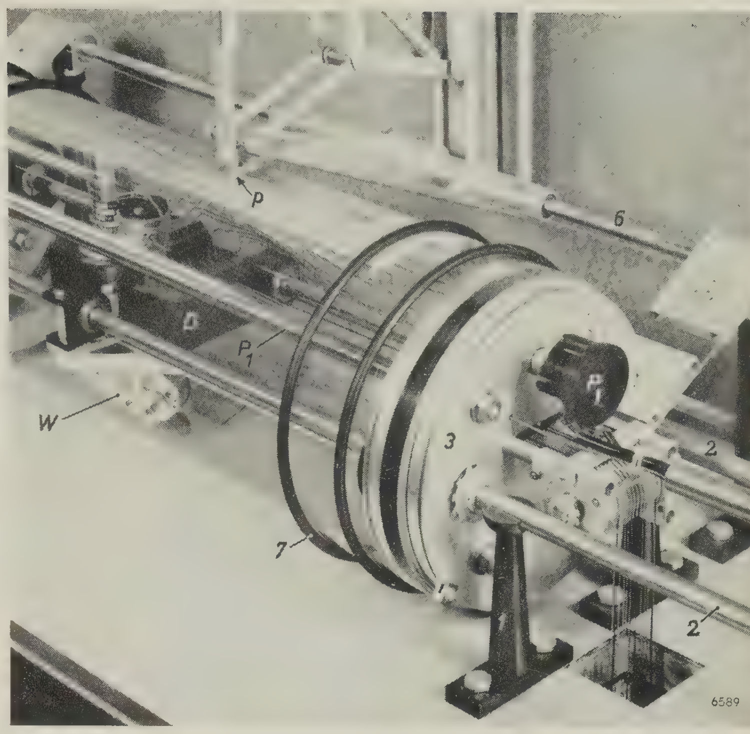


Fig. 10. The drum as seen from the control desk. The letters and figures have the same meaning as in fig. 9. Right, the trolley supply cables.

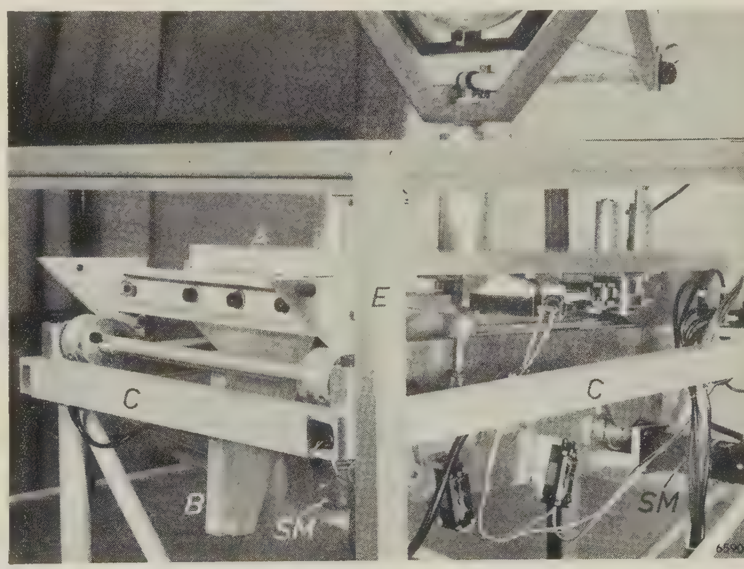


Fig. 11. The lamp holder and the two positional servo-systems. *A* horizontal plate carrying the lamp holder and the azimuth system. *B* vertical plate (joined rigidly to *A*) which carries the elevation system. The whole assembly can be turned through a small angle with respect to the frame *C*, without disturbing the lamp. *SM* positional servo-motors; the motor on the right is for the elevation system. *E* frame of dust-free cabinet.

The lamp holder and the positional servo-systems

The lamp holder and its positional servo-systems are mounted on two mutually perpendicular plates which are rigidly interconnected (*fig. 11*). The horizontal plate carries the lamp holder, and each of the plates carries a positional servo-system. The entire assembly is supported by a frame which has the form of a table without a top, and can rotate about an imaginary horizontal axis through the headlamp, at right angles to the line between headlamp and photocell. This makes it possible to adjust the lamp holder accurately with respect to the latter connecting line.

The construction of the lamp holder is shown in *fig. 12*. The lamp is fixed inside a ring by means of three self-centring clamps. The ring is mounted in a horseshoe-shaped bracket. The beam pattern can be adjusted "horizontally" by turning the ring in

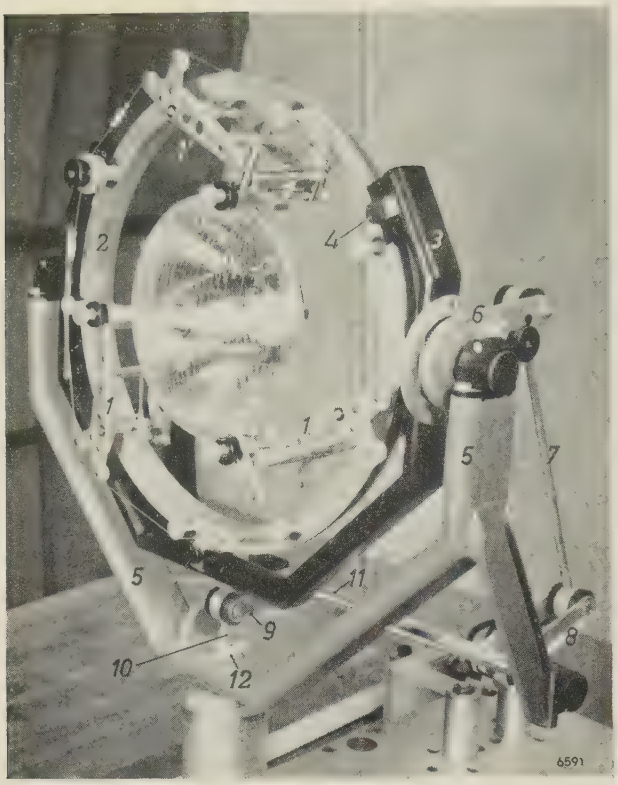


Fig. 12. The lamp holder. *1* self-centring clamps for holding the lamp in position. *2* ring which can turn in bracket *3*. After the appropriate alignment is found, the ring is locked with screws *4*. *5* fork in which *3* is mounted. *6-10* levers and rods which transmit the shaft rotation of the elevation servo-motor to the bracket, etc. Levers *8* and *9* are mounted on the horizontal spindle *11*. The rod *10* passes through the hollow shaft *12* of the fork (cf. fig. 13).

relation to the bracket. Once the right setting has been found the ring is locked in that position.

The bracket is in its turn mounted on bearings in a fork. The line through both bearings is horizontal and passes through the centre of the lamp. The servo-motor which ensures that the elevation of the lamp corresponds to the angle of rotation of the drum can turn the bracket in its bearings by means of a system of rods and levers (see *fig. 13*).

This transmission system is designed so that one of the rods is vertically in line with the centre of the lamp holder and fits into the hollow shaft of the fork. This rod, which moves vertically when the lamp is turned about its horizontal axis, is composed of two sections in line, connected by a coupling. The latter allows relative rotation of the two sections — and hence rotation of the lamp holder — but constitutes a rigid joint for translational movement.

The bottom of the rod is hinged to a lever, one end of which has the form of a toothed sector. The lever is actuated via a gear transmission by the above-mentioned servo-motor.

For varying the azimuth of the lamp, no such complicated mechanism is necessary. In this case a lever with toothed sector is mounted directly at the bottom of the fork. This lever is driven in the same way as the other by the azimuth servo-motor.

The positional indicators showing the state of adjustment of azimuth and elevation are potentiometers (P_2 in fig. 3), whose sliding contacts are driven via a separate transmission by the relevant lever with toothed sector.

For this purpose the levers have a sector without teeth at their other end, the movement of which is transmitted to a drum by means of two metal bands. The movement of this drum is transmitted with great precision to the potentiometer by a system of gears (*fig. 14*).

In this way the required accurate transmission between the elevation and azimuth shafts and the appertaining potentiometer is achieved with the minimum of precision gearing. High accuracy as regards angles is required in this transmission be-

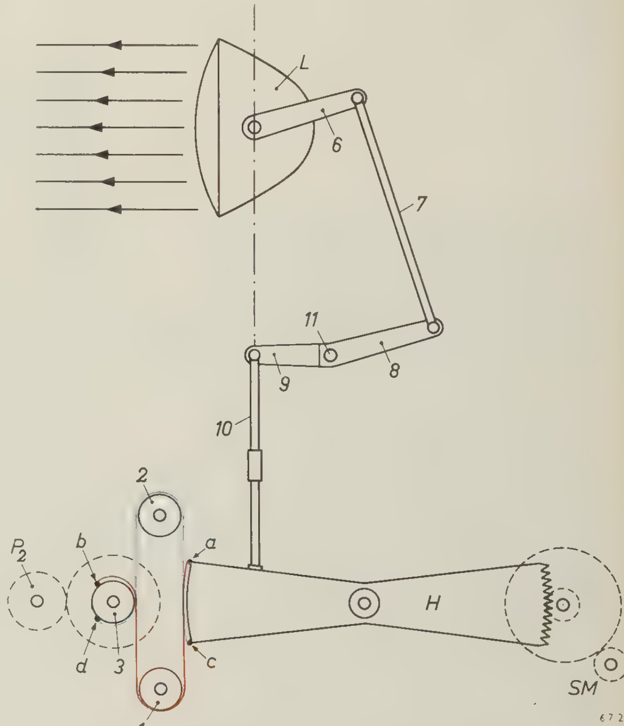


Fig. 13. Illustrating the method of transmitting the shaft rotation of the elevation servo-motor *SM* to the lamp. *L* lamp. *6*, *8* and *9* levers. *7* and *10* rods. *11* spindle on which *8* and *9* are mounted (cf. fig. 12). The rod *10* consists of two parts which, for the azimuthal movement, can rotate relative to each other about the common axis. *H* lever, having a toothed sector on the right and a plain sector on the left. The movement of *H* is transmitted to positonal potentiometers P_2 by two metal bands. One band (red) runs from point *a*, where it is fixed to the sector, over roller *1* to point *b* on drum *3*. The other (blue) runs from *c* over *2* to *d*. The spindle of *3* is fitted with a gear wheel which, via a second gear, rotates the shaft of potentiometer P_2.

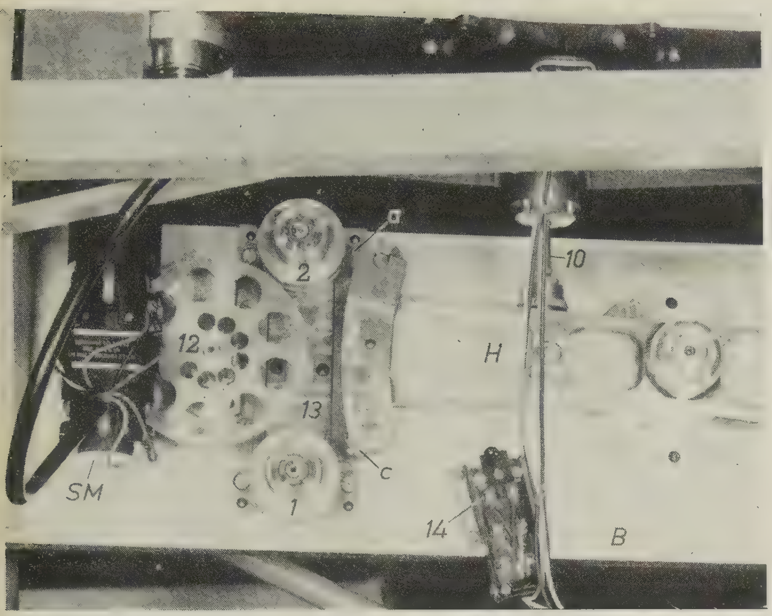


Fig. 14. Transmission of the elevation coordinate to the relevant positional potentiometer. The letters and figures have the same meaning as in fig. 13. The roller *3* in the latter figure is located behind the large gear wheel *12*. Rollers *1* and *2* are not mounted on the vertical plate *B* (cf. fig. 11) but on a brass strip *13*, secured only in the middle to *B*. The suitable choice of materials and dimensions ensures that the strip is not stressed too much or too little. If *H* is in danger of being turned through too wide an angle, end-switch *14* cuts out the elevation servo-motor. *SM* is the azimuth motor.

cause any error will not automatically be corrected. This precision is not demanded from the gears at the motor side, since they do not affect the positional accuracy.

The control desk

As may be seen in fig. 8, a control desk is situated beside the table on which the drum is mounted. The control desk comprises the following components.

a) The main switch, and the switches for the positional servo-motors and the driving motor (in fig. 3 *SM* and M_1 respectively).
b) Selector switches for presetting the reference voltage E_r, and hence the desired value of the luminous intensity.
c) Potentiometers for slightly modifying the alignment of the lamp holder in both coordinate directions without changing the position of the trolley relative to the recording drum.

If the stylus is set on the recording paper at the zero point of the coordinate system, these potentiometers can be used to make the axial direction of the beam coincide with the line between photocell and lamp.

d) A switch for shifting the zero point of the elevation coordinate by a fixed amount, so that the distribution diagrams of the dipped beam and the main beam of a car headlamp can be recorded one below the other on a single sheet of paper, without having to reset the lantern.
e) A galvanometer for checking, before recording an isolux curve, whether the illumination on the photocell roughly corresponds to the value for which the curve is required. The trolley and the drum, and thus also the lamp coupled with them, must be set in such a way as to satisfy this condition. If the deviation is excessive, the apparatus will not automatically "home" on the required isolux curve.
f) Potentiometers for varying the gain in the control loop and the damping. This facility is necessary in view of the above-mentioned fact that the transfer function contains the factor $R_p(E)$, the value of which differs for each different isolux curve. Even if this were not so, it would still be desirable to have some means of varying the gain in connection with the automatic compensation of the variations in K_E: this is most effective when the range of loop gain has a specific position between the minimum and maximum limits of amplification.

The loop transfer function derived from the elements

The remainder of this article will now deal in control-engineering terms with the various components of the isocandela-diagram recorder, regarded as a control loop. We shall consider successively the following elements (cf. figs 3 and 4):

1) The photocell and associated circuit (including the circuit which compares the output signal with the reference signal).
2) The amplifier (A_1) and the control motor M_2.
3) The drive of the drum by the trolley wheel.
4) The positional servo-systems.
5) The lamp (beam pattern).

We shall then derive the formula for the loop transfer function from the transfer functions of these elements, and show that, as far as stability considerations are concerned, the formula can permissibly be reduced to the form of equation (1).

In deriving the transfer functions of the various components we shall treat the latter as linear elements, although some of them are by no means so. The approximation is entirely justified, however, as far as concerns the frequencies and amplitudes occurring in the loop when the instrument is in the process of recording an isocandela curve.

Photocell and associated circuit

The photocell used in the recorder is a selenium barrier-

layer cell. Its spectral sensitivity is made equal to that of the human eye by means of filters. The spectral composition of the light can therefore be changed without having to make a separate calibration for finding the correct lux value. A drawback of barrier-layer cells is their rather low sensitivity (about 0.5 μA/lux in the present case), so that considerable amplification is necessary.

The circuit is represented schematically in *fig. 15*. The dotted square encloses the equivalent electrical circuit of the photocell. This comprises a current source, a capacitance C, representing the capacitance of the barrier layer, in parallel with a resistance R_p, which is the internal "leakage resistance" of the cell. The current i_c from the source is proportional to the illumination E. Since the value of the resistance R_p is not constant — it decreases with increasing E — neither the current in an external network nor the terminal voltage is in general

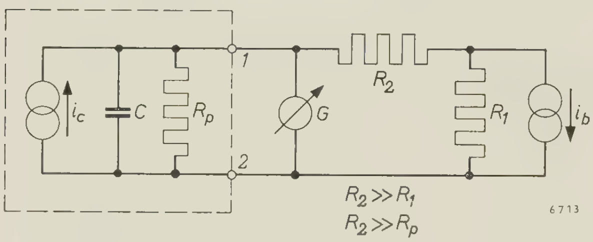


Fig. 15. Equivalent electrical circuit of the photocell (inside the dotted rectangle) and external circuit (compensation circuit). i_c photocurrent. C internal capacitance and R_p internal leak resistance of photocell. i_b compensation current. R_1 and R_2 resistors. G galvanometer. The current i_b is set to a value such that the voltage between the terminals *1* and *2* of the photocell is zero.

proportional to E (see *fig. 16*). To eliminate the influence of R_p, steps must be taken to make the terminal voltage zero. For that purpose the cell is incorporated in a compensation circuit, consisting of the current source i_b and the resistors R_1 and R_2. G is the null instrument. When the value of i_b is adjusted so that the voltage between the terminals *1* and *2* of the photocell is zero, we can write:

$$i_c = \frac{R_1}{R_1 + R_2}\, i_b \,. \quad \ldots \ldots \quad (2)$$

If we make $R_2 \gg R_1$, then $i_b \gg i_c$, and the value of i_b is high enough for easy measurement. At the same time i_b is proportional to E.

The current i_b is also very suitable as a reference signal; in the control loop, then, the compensation circuit functions at the same time as an error detector. Moreover, the current i_c is practically independent of temperature, so that there is no danger that the reference signal will no longer correspond to the desired illumination when the room temperature changes. (This does not apply at very low illuminations, owing to the fact that the highly temperature-dependent dark current then constitutes a significant fraction of the total current.)

For the purpose of calculating the transfer function K_1G_1 of the photocell and compensation circuit together, we should now consider how the output signal ε of the compensation circuit (cf. fig. 4) — i.e. the voltage appearing between the terminals of the photocell upon a change in the illumination — depends on the (small) difference ΔE between the actual illumination and that which corresponds to the preset value of i_b. We can at once put $G_1 = 1$, for at the low frequencies with which we are concerned the frequency dependence of the photocell (characteristic time R_pC) is of no consequence.

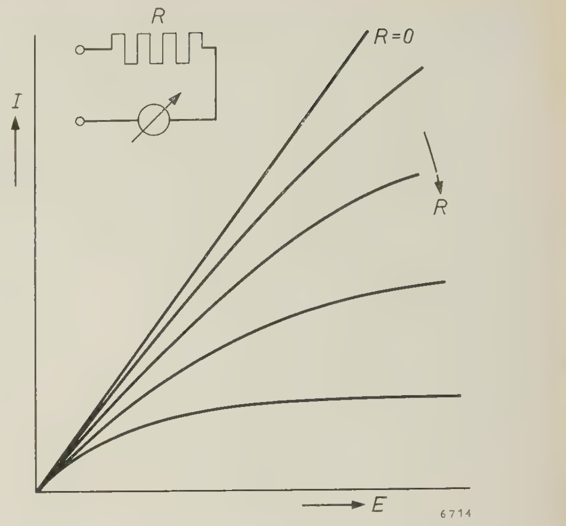


Fig. 16. The current I in the external circuit of a barrier-layer photocell (photovoltaic cell) as a function of the illumination E for various values of the resistance R in that circuit. If R is zero, I is equal to the photocurrent i_b (cf. fig. 15) and proportional to E. The deviation from linearity is greater the larger the value of R. The curve applicable to a very large R has of course virtually the same shape as the E-V characteristic (V is the open-circuit terminal voltage).

Assuming then that Δi_c is the change in i_c corresponding to ΔE, we have:

$$\varepsilon = \frac{(R_1 + R_2)R_p}{R_p + R_1 + R_2}\, \Delta i_c \,. \quad \ldots \ldots \quad (3)$$

Since R_2 is large not only compared with R_1 but also compared with R_p, the right-hand side can be approximated by $R_p \Delta i_c$. The desired transfer function $(\varepsilon/\Delta i_c)_{\omega=0}$ is therefore not constant but depends on the illumination: if E rises from 0.25 lux to 40 lux, K_1 is reduced by a factor of 2.

Referring to the V-I characteristics of the photocell, which are presented in *fig. 17*, we shall now analyse the properties of the compensation circuit (fig. 15) in somewhat more detail.

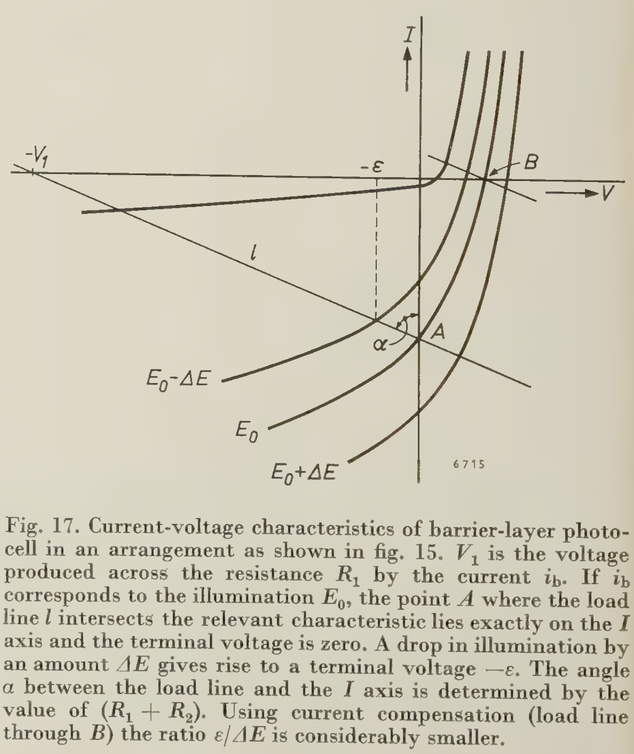


Fig. 17. Current-voltage characteristics of barrier-layer photocell in an arrangement as shown in fig. 15. V_1 is the voltage produced across the resistance R_1 by the current i_b. If i_b corresponds to the illumination E_0, the point A where the load line l intersects the relevant characteristic lies exactly on the I axis and the terminal voltage is zero. A drop in illumination by an amount ΔE gives rise to a terminal voltage $-\varepsilon$. The angle α between the load line and the I axis is determined by the value of $(R_1 + R_2)$. Using current compensation (load line through B) the ratio $\varepsilon/\Delta E$ is considerably smaller.

As can be seen, the V-I curves (each curve relates to one value of illumination) pass through three quadrants. Using the photocell without an external voltage source, the operating point is in the fourth quadrant (bottom right). Where, as in our case, the photocell is used in a compensation circuit with an auxiliary voltage V_1 — the voltage produced across the resistance R_1 by the current i_b — the operating point for an illumination E_0 is found at the point where the load line intersects the curve relating to the illumination concerned. The load line in this case is the straight line through the point $(-V_1, 0)$ which cuts the negative I axis at an angle $\alpha = \tan^{-1}(R_1 + R_2)$. If E_0 and the current i_b correspond to one another, the operating point lies exactly on the negative I axis (point A).

When a small change $-\Delta E$ occurs in the illumination, the new operating point is found to be the point where the same load line intersects the characteristic for $E_0 - \Delta E$. The terminal voltage ε now appearing across the photocell is the abscissa of the new operating point. To obtain the maximum possible voltage ε for a given change ΔE in illumination, it is best to make R_2 large, in which case the angle α is large.

Finally, it can be seen from fig. 17 that, for a given slope of the load line, the ratio $\varepsilon/\Delta E$ with the compensation method employed here is appreciably larger than it would be with a method in which the current delivered by the cell were to be made equal to zero. In the latter case the operating point (for E_0) would not be at A but on the positive V axis at B. Here the curves are much closer together, and a change ΔE in the illumination therefore causes only a small change in the terminal voltage.

The amplifier A_1 and the steering motor

The voltage ε that appears at the terminals of the photocell when the illumination differs from the value corresponding to the reference signal is, as we have seen in fig. 3, considerably amplified so that it can be used to drive the steering motor. In order to minimize the influence of interfering signals, the amplifier is designed as a difference amplifier with a high rejection factor [7]). For all frequencies and amplitudes involved, the gain factor of this amplifier has the same value. The amplifier therefore contributes only one constant factor to the transfer function K_2G_2 of the part of the isocandela-diagram recorder that we are now about to discuss. We shall call that factor K_A.

In passing it may be noted that the signal ε is not supplied directly to A_1 but is first converted into a square-wave voltage by a chopper (frequency 400 c/s) to eliminate drift. The amplifier thus supplies an alternating voltage to the control motor. The latter is a two-phase asynchronous induction motor, and thus has two windings on the stator. The output signal from A_1 is supplied to the one winding. The other is supplied with a constant alternating voltage, also of 400 c/s, which differs in phase by 90° with respect to the output signal from A_1. This method of supply makes the torque of the rotor proportional to ε. For simplicity, these particulars have been omitted from fig. 3.

We shall now derive the transfer function of the steering motor from the equation describing the behaviour of the motor. The torque T supplied by the motor depends both on the supply voltage V_m and on the speed of the motor (the angular velocity Ω of the shaft). To a first approximation, then:

$$T(V_m,\Omega) = \left(\frac{\partial T}{\partial V_m}\right)_\Omega V_m + \left(\frac{\partial T}{\partial \Omega}\right)_{V_m} \Omega. \quad \ldots \quad (4)$$

The value of the differential quotient $\partial T/\partial V_m$ for the case $\Omega = 0$ is the *torque constant* K_m. The differential quotient $\partial T/\partial \Omega$ is negative in the case of servo-motors: as the motor speed increases, the torque decreases in a manner that corresponds formally to the damping caused by a viscous liquid (opposing torque proportional to Ω). The negative value of $dT/d\Omega$ in the case $V_m = 0$ is therefore called the *damping coefficient* and is denoted by the symbol f_m. Let the total moment of inertia around the motor shaft be J_1 and the total viscous damping f_1 (both of motor and load together), then:

$$K_m V_m - f_1\Omega = J_1\, d\Omega/dt. \quad \ldots\ldots \quad (5)$$

If we substitute the complex quantities $\bar{V}_m$ and $\bar{\Omega}$ for V_m and Ω following the practice in control-system analysis [8]), equation (5)becomes:

$$K_m\bar{V}_m - f_1\bar{\Omega} = J_1\, j\omega\bar{\Omega},$$

so that we find for the transfer function of the motor:

$$\frac{\bar{\Omega}}{\bar{V}_m} = \frac{K_m}{f_1 + J_1 j\omega} = \frac{K'}{1 + j\omega\tau_1}, \quad \ldots\ldots \quad (6)$$

where $\tau_1 = J_1/f_1$ and $K' = K_m/f_1$.

In arriving at this formula, however, we have not yet entirely reached our objective. In order to be able to adjust the damping to a suitable value, the motor shaft is coupled to the shaft of a tacho-generator, which generates a voltage proportional to the speed. This output voltage, amplified if necessary, is fed back to the terminals of the motor. This produces an opposing torque which is proportional to the speed, so that here too we can speak of viscous damping. The transfer function of the tacho-generator is simply equal to the constant ratio K_t between the (amplified) output voltage and Ω (*fig. 18*). The transfer function of the motor and tacho-generator combined is therefore:

$$\frac{\bar{\Omega}}{\bar{V}_m} = \frac{K'/(1 + j\omega\tau_1)}{1 + K'K_t/(1 + j\omega\tau_1)}. \quad \ldots\ldots \quad (7)$$

After manipulation and introduction of the factor K_A, the transfer function of the amplifier A_1, this expression reduces to:

$$K_2G_2(j\omega) = \frac{K_2}{1 + j\omega\tau_2}, \quad \ldots\ldots \quad (8)$$

where $\tau_2 = \tau_1/(1 + K'K_t)$ and $K_2 = K_AK'/(1 + K'K_t) \approx 1/K_t$. The characteristics of elements having a transfer function of the form $K/(1 + j\omega\tau)$ were discussed at some length in the articles quoted above [4]).

The drive of the drum

We shall now consider how the position of the steering rod varies with respect to the surface of the drum when the rod is

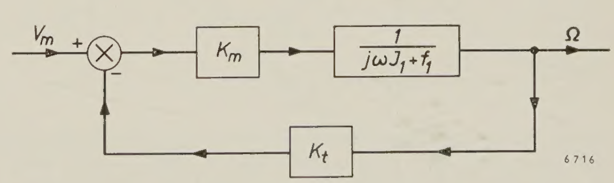


Fig. 18. Block diagram of steering motor with tacho-generator feedback circuit. V_m motor supply voltage. Ω angular velocity of motor shaft. K_m torque constant of motor. f_1 total viscous damping. J_1 moment of inertia of motor and load together. K_t ratio between Ω and the voltage delivered by the tacho-generator.

---

7) See e.g. G. Klein and J. J. Zaalberg van Zelst, General considerations on difference amplifiers, Philips tech. Rev. **22**, 345-351, 1960/61 (No. 11).

8) See e.g. M. van Tol, Philips tech. Rev. **23**, 1961/62, No. 4, pages 109 and 112.

turned through an angle Θ_s (for simplicity we can just as well treat the drum as the flat table in fig. 3). We shall characterize this position as the distance x from the rod to the original line of travel. This distance consists of two components. In the first place there is a component x_1, the time derivative of which is proportional to the peripheral velocity v of the wheel rolling over the surface and to the sine of the angle Θ_s between the old and the new line of travel. For small values of Θ_s we can thus write:

$$\frac{dx_1}{dt} = v\Theta_s . \quad \quad (9)$$

The second component arises from the above-mentioned fact that the wheel is in contact with the drum not in line with the steering rod but at a distance a behind it. A displacement Θ_s of the steering rod causes in the x direction a displacement x_2 of magnitude $a \sin \Theta_s$ (see *fig. 19*). For small Θ_s we therefore have $x_2 = a\Theta_s$. The displacement $a(1 - \cos\Theta_s)$ in the direction perpendicular to x can be neglected for small values of Θ_s.

The equation that gives the relation between x $(= x_1 + x_2)$ and Θ_s is thus

$$\frac{dx}{dt} = v\Theta_s + a\frac{d\Theta_s}{dt} . \quad \quad (10)$$

Replacing x and Θ_s by the complex quantities [8] $\overline{x}$ and $\overline{\Theta}_s$, we find:

$$j\omega \overline{x} = v\overline{\Theta}_s + a\, j\omega\, \overline{\Theta}_s , \quad \quad (11)$$

so that

$$\frac{\overline{x}}{\overline{\Theta}_s} = \frac{v + j\omega a}{j\omega} = v\tau_0 \frac{1 + j\omega\tau_3}{j\omega\tau_0} , \quad \quad (12)$$

where $\tau_3 = a/v$ (cf. p. 281) and τ_0 is again the unit of time.

We have still not found, however, the transfer function K_3G_3 of the relevant part of the recorder. We have to relate x not to the angular position of the steering rod but to the angular velocity Ω of the shaft of the steering motor (see eq. 7). This means first of all that we have to replace Θ_s by $d\Theta_s/dt$, and thus the quantity $\overline{\Theta}_s$ in (12) by $j\omega\overline{\Theta}_s$, and further that we must take into account the gear transmission ratio n_1 between the two shafts. We then find:

$$K_3G_3(j\omega) = \frac{v\tau_0^2}{n_1} \frac{1 + j\omega\tau_3}{(j\omega\tau_0)^2} . \quad \quad (13)$$

Fig. 19. The point of contact of the drive wheel L on the drum is not in line with the steering rod S but at a small distance a behind the axis of the rod. Consequently, when S is turned through the angle Θ_s the distance between the rod and the old line of travel l_1 consists not only of a component x_1 increasing proportionally with time but also of a constant component x_2 of magnitude $a \sin \Theta_s$.

Fig. 20 shows the relevant Bode diagram, approximated by straight lines. The diagram consists of two parts of slope -2 and -1. The break lies at the frequency $\omega_3 = 1/\tau_3$. The phase shift at this frequency is $-135°$. Since $\omega_3 = v/a$, we can therefore shift the break towards a lower frequency by increasing the distance a or by reducing the peripheral velocity v of the wheel. It can be derived from (12) that, if v is varied, the break moves along the line having the slope -1, and if a is varied the break moves along the line with the slope -2.

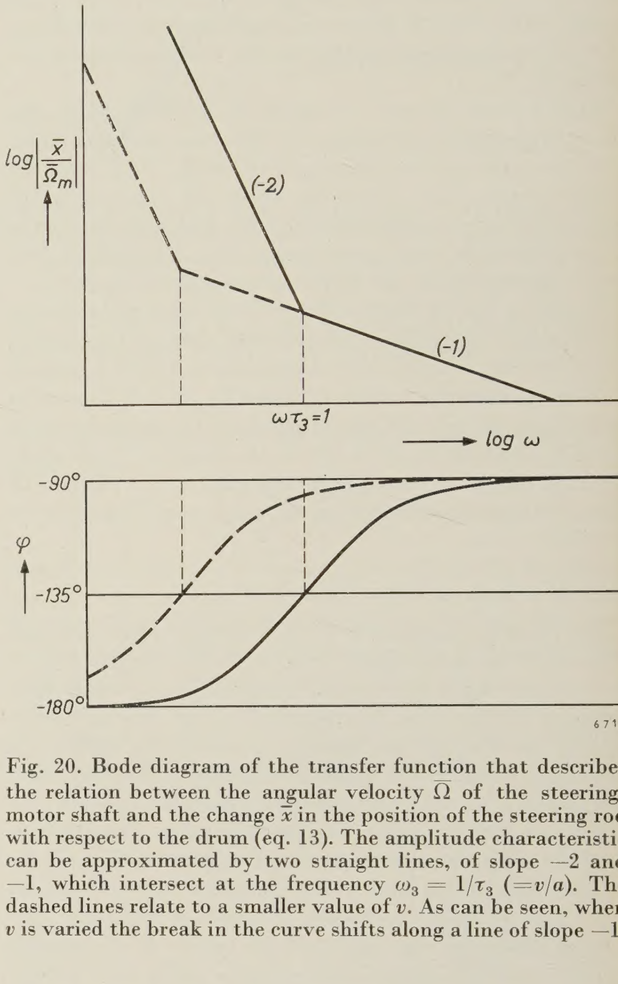


Fig. 20. Bode diagram of the transfer function that describes the relation between the angular velocity $\overline{\Omega}$ of the steering-motor shaft and the change $\overline{x}$ in the position of the steering rod with respect to the drum (eq. 13). The amplitude characteristic can be approximated by two straight lines, of slope -2 and -1, which intersect at the frequency $\omega_3 = 1/\tau_3$ $(=v/a)$. The dashed lines relate to a smaller value of v. As can be seen, when v is varied the break in the curve shifts along a line of slope -1.

The positional servo-systems

The most complicated part of the isocandela-diagram recorder from the control-engineering point of view is that formed by the two positional servo-systems, which transmit the movements of the drum to the lamp. Since the systems are virtually identical, it will be sufficient to discuss only one of them, and for deriving the transfer function of the whole instrument it will be permissible to assume that there is only one positional servo-system.

A block diagram of one of the systems is given in *fig. 21*. It can be seen that, apart from the feedback from output to input, which makes it possible for the output signal to follow the input signal faithfully, there is also an inner loop. The latter relates to the servo-motor (*SM* in fig. 3) which, like the steering motor, is provided with a tacho-generator feedback circuit (cf. fig. 18). In this case, however, the output voltage from the tacho-generator is not directly returned to the motor but first passes through a high-pass filter. The transfer function of this filter is $j\omega\tau_4/(1 + j\omega\tau_4)$, where τ_4 is equal to the product

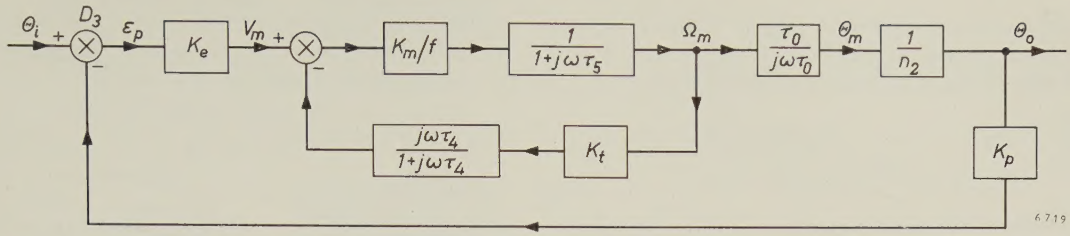


Fig. 21. Block diagram of each of the servo-mechanisms which transmit the positional changes of the drum to the lamp (cf. fig. 3). Θ_i electric input signal corresponding to the relevant coordinate of the drum. Θ_o output signal, one of the coordinates of the lamp. K_p transfer function of the position pick-off P_2. D_3 difference circuit. ε_p difference signal. K_e gain factor of amplifier A_2. V_m servo-motor supply voltage. Apart from their subscripts, K_m, f, J, K_t and Ω_m have the same meaning as in fig. 18, but now relate to the servo-motor. For τ_5 see eq. (14). n_2 ratio of the rotation of the servo-motor shaft to the rotation of the lamp. τ_4 time constant of high-pass filter in the inner control loop (tacho-generator feedback).

of the resistance and capacitance which are the main components of the circuit concerned. The reason for the presence of this filter will be made clear after we have arrived at the transfer function of the complete open loop of fig. 21.

In the same way as we found the transfer function of the closed steering-motor loop (eq. 7) from that of the open loop (eq. 6), we find for the transfer function $\overline{\Omega}_m/\overline{V}_m$ of the closed inner loop:

$$\frac{\overline{\Omega}_m}{\overline{V}_m}=\frac{K_m}{f}\,\frac{1+j\omega\tau_4}{1+j\omega(\tau_4+\tau_5+K''\tau_4)-\omega^2\tau_4\tau_5}, \quad (14)$$

where $\tau_5=J/f$ and K'' is the loop gain K_mK_t/f of the inner loop.

The open-loop transfer function of the whole positional servo-system is thus:

$$\frac{K_p\overline{\Theta}_o}{\overline{\varepsilon}_p}=\frac{K_pK_mK_e\tau_0}{n_2f}\,\frac{1+j\omega\tau_4}{j\omega\tau_0\{1+j\omega(\tau_4+\tau_5+K''\tau_4)-\omega^2\tau_4\tau_5\}}. \quad (15)$$

Since K'' has been chosen to be large, in the discriminant of the quadratic form occurring in the denominator of (15) we have:

$$(\tau_4+\tau_5+K''\tau_4)^2 \gg 4\tau_4\tau_5 .$$

This form can therefore be resolved to a good approximation into the factors $(1+j\omega K''\tau_4)$ and $(1+j\omega\tau_5/K'')$, so that:

$$\frac{K_p\overline{\Theta}_o}{\overline{\varepsilon}_p}=K'''\tau_0\,\frac{1+j\omega\tau_4}{j\omega\tau_0(1+j\omega K''\tau_4)(1+j\omega\tau_5/K'')}, \quad (16)$$

where $K'''=K_pK_mK_e/n_2f$. The Bode diagram, in a linear approximation, is given in *fig. 22*. The slope of successive sections is —1, —2, —1 and again —2. The breaks lie at the frequencies at which $\omega K''\tau_4=1$, $\omega\tau_4=1$ and $\omega\tau_5=K''$. Choosing the gain so that it is equal to unity at a frequency ω_0, a value between the two last-mentioned breaks, the phase margin is then $\geq 45°$, which means that the closed loop is sufficiently stable.

The significance of the above-mentioned filter in the tacho-generator feedback circuit is now clearly apparent from fig. 22. Without that filter the Bode diagram would have the form shown by the dashed lines (together with the full lines joining them). The filter evidently leaves the characteristics unchanged at high frequencies, but at low frequencies it considerably increases the gain. The reason for this may be inferred from the block diagram: for high frequencies the filter may be regarded as not present, i.e. as a closed switch, and for low frequencies as an open switch. In the latter case there is therefore no feedback and the function $\overline{\Omega}_m/\overline{V}_m$ is obviously larger.

The inclusion of the high-pass filter in the inner loop thus has the effect of increasing the value of the open-loop transfer function $K_p\overline{\Theta}_o/\overline{\varepsilon}_p$ for the low frequencies and of correspondingly reducing the velocity error of the systems [9]) without enlarging the bandwidth, i.e. without increasing the influence of disturbances.

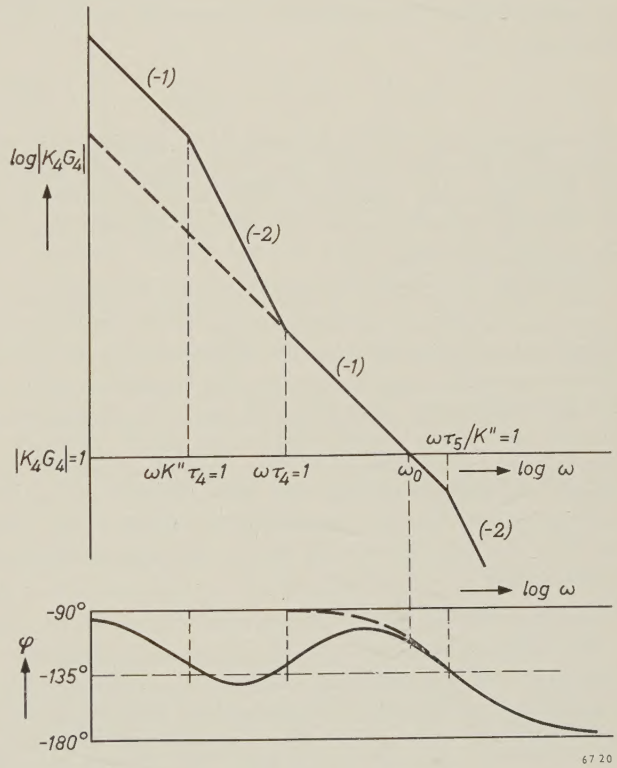


Fig. 22. Bode diagram of each of the positional servo-systems. The dashed lines would apply if the high-pass filter were omitted from the inner loop (cf. fig. 21). With the filter the gain at low frequencies is greater for the same bandwidth, and hence the velocity error smaller.

[9]) Just as in the case of a proportional controller (cf. p. 110 of the first and p. 151 of the second article cited under [4])) the static error (offset) decreases as $KG(0)$ increases, in the case of the servo-system as considered here the steady-state velocity error is smaller the higher is the gain. This is an example of one of the methods for improving a control system, discussed in the second article mentioned in footnote [4]). It can be shown that the high-pass filter in the feedback circuit has the same effect as an integrating element.

Taking into account that $K''\tau_4 \gg \tau_5/K''$ and $K'''\tau_4 \gg 1$, we can write the formula derived from (16) for the closed-loop transfer function K_4G_4 of the positional servo-system as

$$K_4G_4 = \frac{\Theta_o}{\Theta_r} = \text{const.}\ \frac{1 + j\omega\tau_4}{1 + j\omega\tau_4 - \omega^2\tau_4 K''/K''' - j\omega^3\tau_4\tau_5/K'''}. \quad \ldots \quad (17)$$

If we now choose the gain not merely so that ω_0 lies between the breaks in the curve at the frequencies for which $\omega\tau_4 = 1$ and $\omega\tau_5 = K''$, but moreover so that ω_0 lies close to the latter frequency, and if we have satisfied the requirement that $\omega_0\tau_4 \gg 1$, the denominator of (17) can be represented approximately as the product of the factors: $[1 + j\omega\tau_4(1 - K''/K'''\tau_4)]$ and $[1 + j\omega K''/K''' - (1 + K''/K'''\tau_4)\tau_5\omega^2/K''']$. We can then simplify (17) to:

$$K_4G_4 = \text{const.}\ \frac{1 + j\omega\tau_4}{[1 + j\omega\tau_4\,\tau_5/K'''\tau_6^2]\ [1 + 2\,\zeta\, j\omega\tau_6 - \omega^2\tau_6^2]}, \quad \ldots\ldots \quad (18)$$

where $K'''\tau_6^2 = \tau_5(1 + K''/K'''\tau_4)$ and $2\zeta = K''/K'''\tau_6$, and furthermore $\tau_6 \approx \omega_0^{-1}$.

From the assumptions $\tau_6 \approx \tau_5/K''$ and $\tau_4 \gg \tau_6$ it follows that $\tau_5/K'''\tau_6^2 \approx 1$, so that in our case, at least as far as stability is concerned, the first factor of the denominator can be cancelled against the numerator. The formula for G_4 then becomes:

$$G_4 = \frac{1}{1 + 2\zeta\, j\omega\tau_6 - \omega^2\tau_6^2}. \quad \ldots\ldots \quad (19)$$

(In practice the case with the two complex conjugate roots is preferred to the other because then the system is not aperiodically damped but exhibits oscillation. If the overshoot can be kept within bounds, a faster response can be obtained.)

The beam pattern of the lamp

The transfer function (1) of the whole recorder contains the factor K_E, the gradient of the illumination at the point in the patch of light on the screen where the photocell is situated. The reason for this is readily apparent. The signal delivered by the photocell upon a slight shift $\Delta\Theta_o$ (eq. 17) in the angular position of the lamp is proportional to the change ΔE of the illumination, i.e. proportional to the product of the positional change and the gradient K_E. The ratio $\Delta E/\Delta\Theta_o$, the only transfer function not yet obtained, is thus equal to K_E. In fig. 7 we saw how the value of K_E may fluctuate along one isolux contour.

The transfer function of the whole loop

Now that we have found the transfer functions of all the elements of the isocandela-diagram recorder, we can write the transfer function KG of the whole control loop. The factors that are not dependent on ω will not, in so far as they are constant, be explicitly mentioned, but two other factors will be, namely K_E and R_p (the latter being the internal leakage resistance of the photocell). We thus find:

$$KG = \text{const.}\ K_E R_p\ \frac{1}{1 + j\omega\tau_2}\ \frac{1 + j\omega\tau_3}{(j\omega\tau_0)^2}\ \frac{1}{1 + 2\zeta j\omega\tau_6 - \omega^2\tau_6^2}. \quad \ldots \quad (20)$$

In this expression, apart from the quantities already mentioned,

τ_2 is the time constant of the control motor (with tacho-generator feedback): $\tau_2 = J_m/(f_1 + K_mK_t)$,

τ_3 the quotient a/v of the distance between axis and point of contact and the peripheral velocity of the wheel,

τ_6 the reciprocal of the cross-over frequency ω_0, above which the gain of the positional servo-system falls below unity.

As stated, for considerations of stability the complete formula for KG can be considerably simplified. The reduction of (17) to (19) was already a substantial simplification, but a further one is possible. The time constant τ_2 is so small that the frequency ω_2 $(= 1/\tau_2)$ is appreciably larger than ω_0. Its effect on the part of the Bode diagram of interest from the point of view of stability can therefore be disregarded. (Since τ_2 is very small its contribution to a transient also dies out very rapidly.)

The simplified form of (20), which is sufficient for a stability analysis and has already been encountered as equation (1), is thus:

$$KG \approx \text{const.}\ K_E R_p\ \frac{1 + j\omega\tau_3}{(j\omega\tau_0)^2\,\{1 + 2\zeta j\omega\tau_6 - \omega^2\tau_6^2\}}.$$

The stability considerations themselves were dealt with when the latter formula was first presented.

Summary. The luminous-intensity pattern (an array of isocandela curves) of a beamed light-source is determined in principle by finding curves of constant luminous intensity (isolux contours) on a screen set up in front of the lamp. Such a curve joins all the points corresponding to those directions in which the luminous intensity is the same. An instrument is described which traces the isolux curves automatically, reduced in scale by about 30×. The light detector (a barrier-layer photocell) remains in a fixed position while the angular setting of the light source is varied. The entire instrument can be regarded as a closed control loop. The driving element is a single-wheel "trolley", which causes the drum to which the recording paper is fixed to turn about its axis and propels a stylus in the direction of that axis, the position of the stylus on the paper being transmitted by servo-systems to the lamp. The difference between the photocell signal and a reference signal is used, after amplification, to actuate the motor which steers the trolley. The feedback which, via the steering motor, the trolley and the drum, exists between the photocell and the lamp automatically ensures that the lamp, and therefore the stylus on the paper, can only take up those positions that correspond to the preset value of luminous intensity. The stylus thus traces the isolux curve for that value.